FINAL REPORT

Software-Defined Wireless Decentralized Building Management System

ESTCP Project EW-201410

JUNE 2018

Anthony Colonnese
Ameresco

Julian Lamb
Paragon Robotics

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REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)* 17-05-2018	**2. REPORT TYPE** ESTCP FINAL REPORT	**3. DATES COVERED** *(From - To)* 01-08-2014 - 28-02-2018
4. TITLE AND SUBTITLE Software-Defined Decentralized Wireless BMS		**5a. CONTRACT NUMBER** W912HQ-14-C-0053
		5b. GRANT NUMBER
		5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) Julian Lamb (Paragon Robotics), Tony Colonnese (Ameresco)		**5d. PROJECT NUMBER** EW-201410
		5e. TASK NUMBER
		5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Ameresco, Inc 111 Speen Street, Ste 410 Framingham, MA 01701	Paragon Robotics LLC 5386 Majestic Pkwy Ste#2 Bedford Heights, OH 44146	**8. PERFORMING ORGANIZATION REPORT** EW-201410
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Environmental Security Technology Certification Program 4800 Mark Center Drive, Suite 16F16 Alexandria, VA 22350-3605		**10. SPONSOR/MONITOR'S ACRONYM(S)** ESTCP
		11. SPONSOR/MONITOR'S REPORT NUMBER(S) EW-201410

12. DISTRIBUTION / AVAILABILITY STATEMENT

Distribution A: unlimited public release

13. SUPPLEMENTARY NOTES

14. ABSTRACT

This report documents the installation and testing of a new BMS architecture which significantly lowers total lifecycle cost to 1/2 that of state-of-the-art competitors in the small building sector, enabling ROIs that make retrofits possible through performance contracts. The results of this project clearly establish the installed costs and energy savings for a range of building sizes and HVAC setups, demonstrating the necessary ROI to justify efficiency projects using this BMS. Installing advanced BMS systems in a larger portion of the DoD small building inventory will generate considerable utility savings for the DoD as well as help meet federal greenhouse emission reduction mandates.

15. SUBJECT TERMS

Software-Defined Decentralized Wireless BMS, Application protocol interface, Building Management System, Current Transformer, HVAC, Industrial Control, Operation and Maintenance

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**	UU	88	Julian Lamb
U	U	U			**19b. TELEPHONE NUMBER** *(include area code)* 330.977.7981

Standard Form 298 (Rev. 8-98)

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ACRONYMS AND ABBREVIATIONS

AFB	Air Force Base
AFCEC	Air Force Civil Engineering Center
API	Application protocol interface
ATO	Authority to Operate
BMS	Building Management System
CE	Civil Engineering
CEIG	Cyber Engineering and Information Group
CT	Current Transformer
dBm	Decibel-milliwatts
DoD	Department of Defense
EO	Executive Order
EPA	U.S. Environmental Protection Agency
ESCO	Energy Service Company
ESTCP	Environmental Security Technology Certification Program
EW	Energy and Water
HVAC	Heating, Ventilation, and Air Conditioning
IAM	Information Assurance Manager
IAQ	Indoor Air Quality
IATT	Interim Authority to Test
ICS	Industrial Control Systems
kW	kilowatt
LAN	Local Area Network
M2M	Machine to machine
M&V	Measurement and Verification
MDIP	Modified DIACAP Implementation Plan
O&M	Operation and Maintenance
PC	Personal Computer
PLC	Programmable Logic Controller
POC	Point of Contact
ROI	Return on Investment
SCIF	Sensitive Compartmented Information Facility
VLAN	Virtual Local Area Network

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ACKNOWLEDGMENTS

The authors thank the Environmental Security Technology Certification Program (ESTCP) for funding this effort and for the support of the program manager (Mr. Tim Tetrault) and program lead (Ms. Sarah Medepalli). Extensive project support was provided by Tinker Air Force Base within the 72d CE (Mr. Al Romero and Ms. Barbara Kochis) and 38th CEIG (Mr. Thanh Alcorn). Air Force Civil Engineering Center (AFCEC) also provided support for obtaining the necessary Authority to Operate (ATO).

Mr. Julian Lamb with Paragon Robotics, and Mr. Tony Colonnese with Ameresco were the key project drivers throughout the project, and were a critical part of its success.

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ABSTRACT

INTRODUCTION AND OBJECTIVE

The potential for energy savings resulting from current state-of-the-art building management systems (BMSs) is well documented. However, in order to achieve the necessary return on investment (ROI) to justify a retrofit project, the installed cost of the system must be low relative to the energy savings achieved. For small buildings (<50,000 sqft), the yearly energy usage is usually too low to justify the high installed costs of current BMSs.

We have demonstrated a new BMS architecture which significantly lowers total lifecycle cost to 1/2 that of state-of-the-art competitors in the small building sector, enabling ROIs that make retrofits possible through performance contracts. The results of this project clearly establish the installed costs and energy savings for a range of building sizes and HVAC configurations, demonstrating the necessary ROI to justify efficiency projects using this BMS.

TECHNOLOGY DESCRIPTION

The demonstrated BMS is built on a sensor and control platform which is unique compared to current state-of-the-art platforms in several ways:

a) Decentralized: each device is capable of running its own high-level software, and is capable of communicating with any other device on the network. This eliminates the need for standalone controllers, which can dominate the overall cost of a BMS for small buildings.

b) Low-cost: the firmware has been specifically designed and optimized to run on ultra-low-cost microprocessors, drastically reducing hardware costs while significantly improving battery life.

c) Class-leading Wireless: a new, proprietary, low-datarate wireless protocol has been developed to specifically improve indoor range, power usage, and cost versus competing systems.

PERFORMANCE AND COST ASSESSMENT

The results from the project show a 25% electricity savings and 45% gas savings were achieved in the test buildings with the retrofit BMS. Furthermore, a BMS retrofit on the entire demonstration building set was calculated to provide a 4.8-year simple payback, easily meeting the 10-year payback needed to allow this technology to be utilized in performance contracting on small buildings.

The 1993 CBECS Federal building survey estimates 45% of DoD floorspace is made up of small buildings, of which only 22% had energy management systems at the time. The demonstrated BMS technology enables the complete retrofit of these remaining small buildings using performance contracting, enabling $200 million in yearly utility savings.

IMPLEMENTATION ISSUES

Several unplanned HVAC equipment outages and building occupancy changes reduced the number of test buildings for the project, however the results from the tested buildings were used to create and validate high-quality simulation models for the remaining buildings, allowing us to obtain good overall data.

PUBLICATIONS

No publications were submitted as part of this project.

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1 INTRODUCTION

1.1 BACKGROUND

In order to improve the return on investment (ROI) of a particular building energy performance upgrade, either a) the lifetime cost of the upgrade must be reduced, or b) the lifetime building energy usage must be reduced. Competing building management system (BMS) solutions tend to focus on reducing energy usage rather than reducing the lifecycle cost of installing, maintaining, and upgrading a BMS installation.

The existing state-of-the-art BMS typically consists of one or more "field controllers" inside a building running the control software. This controller is then connected to sensor and control devices throughout the building typically using twisted-pair wiring. On larger buildings, multiple field controllers must be installed and networked to each other, and then to higher level "network controllers" if a site-wide management system is used. This typical BMS configuration has several distinct limitations versus the demonstrated BMS architecture:

a) Installed Cost: Installing and commissioning a typical BMS is extremely time-intensive and expensive. This cost is especially burdensome in three specific cases: a) small (<50000 sqft) buildings where the cost of the controllers dominate the overall hardware cost of the BMS (74% of all small federal buildings are under DoD control), b) retrofit applications where existing twisted-pair wiring does not exist everywhere in the building, and c) complex HVAC setups, with combinations of multiple HVAC systems such as chillers, boilers, packaged units, and window/space units in the same building, which typically require multiple controllers and extensive integration work.

b) Maintainability/Upgradability: In order to upgrade the typical BMS with improved control algorithms, the field controllers must typically be replaced. As a result, control algorithm improvements are not normally made outside of major improvement projects, since significant energy performance improvements are required to justify the hardware upgrade costs.

c) Scalability: As improved sensor/control technology becomes available or becomes more cost-effective over time, existing BMS systems cannot easily handle small incremental scaling and typically require significant upgrades to the controllers when additional sensor types are added. This "controller-centric" design fundamentally increases the complexity of any scaling when complete integration is desired, as each controller then needs to be networked together and often times the entire control topology needs to be reconfigured.

d) Energy Auditing: Due to the fundamental bandwidth limitations of twisted-pair bus connections, poor or non-existent wireless performance, and fundamental architecture of the typical BMS, existing BMSs do not collect performance data well enough to provide auditing or measurement and verification (M&V) data for Energy Services Companies (ESCOs) to use. As a result, many buildings resort to a separate auxiliary network of M&V sensors to provide this data. Even when contractual or accuracy requirements require a standalone M&V system for critical measurements, much of the performance data could potentially be collected by a BMS more cost-effectively.

The 1993 CBECS Federal building survey estimates 45% of DoD floorspace is made up of small (<50000 sqft) buildings, of which only 22% had energy management systems at the time. Considering the age of this last survey, the portion of small buildings with energy management systems has most likely increased closer to 40%. Installing advanced BMS systems in this sector would provide at least an 8% energy savings when replacing an optimized non-BMS control system, and more than 30% energy savings when replacing building controls that lack an off-hour energy reduction scheme based on simulations. At a conservative yearly energy cost of $1.40 per sqft, this equates into an opportunity for $60 to $227 million in utility savings per year for the DoD small building inventory alone. Additionally, installing BMSs into a greater portion of small DoD buildings will provide other benefits such as reduced operations and maintenance (O&M) costs.

1.2 OBJECTIVE OF THE DEMONSTRATION

The goal of this demonstration was to validate the economic performance of the technology and address as many barriers to adoption as possible. By reducing energy costs and providing at least a 10-year simple payback period, the demonstrated technology could be widely installed using performance contract vehicles, allowing large-scale adoption at DoD facilities. The following 4 objectives were targeted:

- Demonstrate Energy Savings: The wireless BMS should demonstrate at least 15% energy savings compared to the baseline system with no modern controls.
- Demonstrate ROI: The installed cost of the system should provide a simple payback of less than 10 years, enabling installation using performance contracting.
- Obtain Security Certification: By obtaining an Authority to Operate (ATO) from the US Air Force by the end of the demonstration, adequate security of the technology should be demonstrated.
- Demonstrate Qualitative Performance: All DoD stakeholders should be satisfied with the usability and performance of the system, eliminating any roadblocks to adoption of the technology at DoD sites.

1.3 REGULATORY DRIVERS

Several key drivers are directed at reducing energy usage:

- Title 42, United States Code (U.S.C.), Section 8256, National Energy Conservation Policy Act
- 10 U.S.C. 2911-13, Energy Performance Goals and Plan for Department of Defense
- Public Law (P.L.) 109-58, Energy Policy Act of 2005, August 8, 2005
- 42 U.S.C. 8253, Energy Policy Act of 1992

Additionally, the security of Industrial Control Systems (ICS) is driven by directives from each of the DoD branches. The USAF directive is defined in:

- Engineering Technical Letter (ETL) 11-1: Civil Engineer Industrial Control System Information Assurance Compliance

2 TECHNOLOGY DESCRIPTION

2.1 TECHNOLOGY OVERVIEW

Competing systems have been building on top of legacy platforms for decades, and many modern concerns such as wireless and security have never been properly addressed at a low level. Additionally, communication APIs and hardware power requirements have been constantly growing to handle additional complexities, and result in more expensive systems which are increasingly difficult to design and install.

Halo/S, Paragon's wireless BMS platform, has been designed entirely from the ground up to address the significant limitations of competing systems. This platform encapsulates both data acquisition and controls into a single unified ecosystem. There are 5 main design differences between Halo/S and the architectures of state-of-the-art competing BMS systems:

i) <u>Decentralized</u>: Halo/S has been designed to run on an ultra-low cost (~$0.50) 8-bit 8051 MCU, allowing every sensor and control to be made "smart". This allows sensors, controls, and interfaces to execute their own software and communicate directly with each other, eliminating the need for centralized controllers. This provides unmatched upgradability and scalability, since any arbitrary sensor or control can be added to a Halo/S network without the concern for compatibility, controller input limits, or software limitations. Total hardware cost is also significantly reduced through the elimination of controllers and intermediary devices.

ii) <u>Industry-leading Wireless</u>: A proprietary 915MHz wireless protocol has been developed which provides ultra-low power usage (7-year battery life on AAA batteries). This is achieved with an innovative time-synced network which allows end devices to wake up for only 1ms every 2 seconds to check for incoming requests. The wireless system also provides vastly improved indoor range versus competitors (4x indoor range of Zigbee), through the use of a first-of-its-kind multiple datarate protocol which allows devices to automatically drop down to a slower data rate in order to extend range, while allowing nearby devices to use the fastest rate and reduce congestion. Additionally, a next-gen wireless hardware design provides up to +128dBm wireless link budget, compared to a typical +105dBm budget with competitors.

iii) <u>Software-defined</u>: All hardware devices (sensors/interfaces/controls/gateways/etc.) have an identical Halo/S control module with identical firmware onboard. Actual functionality is then provided by higher level software which can be configured and remapped on-the-fly and over-the-air. This allows unprecedented software upgradability to any network and allows all future upgrades to be done solely with software, reducing the upgrade cost.

iv) <u>Industry-leading Security</u>: AES-256 encryption/authentication is used for all Halo/S communication. Multiple keying allows messages to be encrypted at multiple levels, allowing for advanced security designs with multiple access privileges. The unprecedented network flexibility of Halo/S also allows for many different physical layer connection types, ranging from wireless, TCP, HTTP, I2C, and RS485 options.

v) Merging of Data Acquisition and Controls: By providing built-in data acquisition capabilities to every hardware device, the Halo/S platform effectively merges full-featured data logging and monitoring directly with the BMS capability. For building retrofit projects, initial energy auditing and baselining is typically done on a building prior to installing new controls. The Halo/S platform allows the same sensors to be used for both the auditing phase and the actual control system. Additionally, all devices provide comprehensive monitoring capabilities which can be used for M&V and O&M activities long after the system has been installed. The scalability of the platform also allows the installer to cost-effectively add additional sensors as needed for either M&V or O&M benefits.

Overview of Halo/S Architecture

The fundamental architecture of Halo/S is quite different from existing computing architectures. This new architecture was primarily developed to optimize machine to machine (M2M) communication compared to existing platforms. This fundamental shift in architecture was needed to break the cycle of ever-increasing cost and complexity with competing alternatives in the data acquisition and controls space.

One of the unique differences of the Halo/S architecture is the unification of data and code space. Traditional platforms typically retain data in a separately addressable space from code. If a device needs to communicate with another device, traditional platforms require the code to collect any data parameters relevant to the communication, wrap the instruction and data into a custom packet API, and send it to the peer device. This peer then parses the packet, manually places the relevant parameters into its data space, and executes the necessary code. This architecture requires a custom API for every type of communication, since the device needs to be clearly instructed on which data parameters are relevant for the communication. This fundamentally limits the architecture to a specific set of recognized commands, and critically limits the potential capability for communications outside of this known set of commands.

Halo/S unifies data and code into a single tree structure. When a device needs to communicate with a peer, the Halo/S interpreter is able to automatically copy a subset of its tree at its current location, and then simply transmit that tree subset to another device. The peer device then overlays this incoming tree subset onto its tree and is able to automatically proceed without any specialized API decoding. This architecture completely eliminates the need for any communication APIs, creating a system which is infinitely expandable while exposing 100% of a device's functionality to the network.

Machine Layer

On top of the common firmware for the Halo/S interpreter, each device has a high-level "machine layer" mapping of all input and output hardware it contains. This layer allows all hardware functionality to be fully exposed to the Halo/S network. For example, the machine layer for a temperature sensor would include everything from pin mappings for the A/D converter, calibration equations to expose the temperature reading as a SI value, and logging parameters. Control outputs are similarly configured by this machine layer. This layer is typically fixed for each device, and is not usually modified after device production.

Application Layer

On top of the machine layer, the application layer contains the actual high-level control software. This layer provides a canvas for any arbitrary control programs to reside, ranging from simple alarms to extremely complex programmable logic controller (PLC) algorithms. Many applications can reside on each device, and these applications can also seamlessly interact with each other as well as applications on other networked devices. The application layer is frequently changed by end-users, typically via high-level setup software the user may use during system setup.

Hardware Overview

On top of the Halo/S software platform, a new wireless protocol has been developed by Paragon to drastically improve indoor range and battery life over existing state-of-the-art low datarate wireless protocols such as 802.15.4. A Silicon Labs 8051 MCU is used in combination with a sub-GHz radio, utilizing the 915MHz ISM band for communication. This integrated circuit, along with support components, makes up the OE3x module (see Figure 1), which is then used for every device in the ecosystem. Using an identical module on every device provides several advantages:

1) Module production volumes are higher, reducing assembly and component costs
2) FCC and other wireless certification costs are drastically reduced, as only a few module certifications are needed (separate certifications are needed for antenna variants)
3) Firmware maintenance and support costs are reduced
4) 3rd parties can develop products utilizing the module to create their own fully compatible Halo/S devices

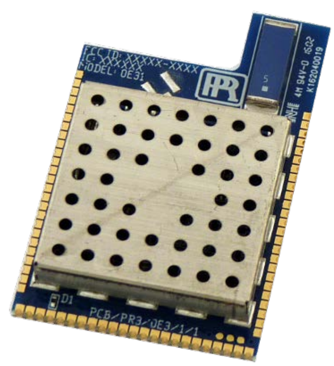

Figure 1. OE3x Module

Hardware Device

All hardware devices used in the BMS are built using a common OE3x module component. Different devices have been created to provide specific input and output functionality. Because all intelligence and configurability of the devices are located entirely in software, only one version of each device is needed to cover all potential HVAC systems. Some of the devices may have lower-end versions in order to strip out some hardware costs not needed for certain applications.

- Gateway: Each building typically requires a gateway to create a wireless network, provide a communication path from the wireless network to a wired, Ethernet network. The gateway also provides storage for logging/trending data sets on its onboard flash memory.

Figure 2. Gateway

- SuperGateway: SuperGateway devices provide additional capability, and manage additional tasks such as automated backups and authentication for users on the system. It also typically serves up the HTML files needed by user workstations.
- Sensors: A wide array of sensor devices are available for use: ambient temperature, ambient humidity, ambient light, occupancy, pipe temperature, airstream temperature, current/power, pulse count, CO2, and many others. All sensors are packaged into a similar base case design.

Figure 3. Typical Sensor

- Thermostats/Temperature Controllers: Thermostats or temperature controllers provide a basic LCD screen and button inputs to allow users to interact with the device. A temperature sensor, humidity sensor, and control relays are present to directly control both low (24V) and high (240V) voltage contacts on equipment.

Figure 4. Thermostat

- 3rd Party Controllers: Controller hardware from 3rd party manufacturers is utilized for more complex equipment control such as AHU, boiler, and chiller controls. Many of these manufacturers now offer low-cost equipment level controls which can be cost-effectively integrated with a Paragon SuperGateway to provide equivalent performance to a full Paragon hardware solution. The additional cost of using this "hybrid" approach on more complex equipment control is minimal, and many times allows local controls contractors to be utilized for installation of the equipment-level controls at DoD sites.

Figure 5. 3rd Party Controller

Software Architecture

The high-level software for the BMS is broadly separated into "equipment control" and "energy control" domains (see Figure 6). The equipment control domain is responsible for the hardware abstraction level for low-level equipment control, and the high-level energy domain controls overall energy savings and site-level strategies. This split allows for several advantages to the overall control topology:

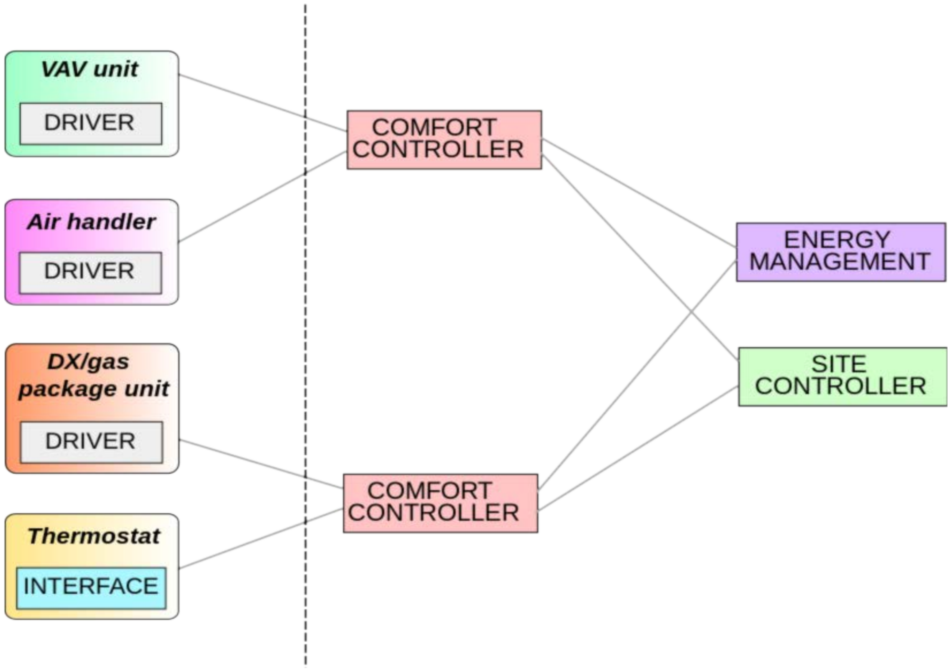

Figure 6. Separation of Energy and Equipment Control

a) Excellent Separation of Duties for ESCO Responsibilities**:** By constraining low-level equipment control and sequences of operation to the "equipment control" domain, ESCOs can retain tight control over energy usage while utilizing local controls contractors to maintain basic operation.

b) Upgrades Can Be Easily Done Without Impacting Energy Efficiency: Equipment level controls can be upgraded to handle changes to HVAC equipment, while exposing the same hardware abstraction API to the energy control domain. During ESPCs, this provides a low-risk upgrade path for equipment-level changes, and helps ensure overall energy performance is unchanged.

c) Energy Control Design Complexity is Drastically Reduced: The energy control domain is further broken down into comfort controllers, energy management blocks, and site controllers. This split allows complex control networks to be broken down into simpler "building blocks". The building blocks can be quickly assembled into a complex system and automatically eliminates all high-level configuration during setup. The task split also makes it much easier to "cut and paste" existing control setups from similar buildings into new HVAC installations, saving considerable time.

High-level Software

All high-level interaction with the demonstrated BMS is done through a web browser using HTML5. Although many competing BMS systems are controlled through browser-based interfaces, Halo/S is done in a much different way. Competing systems typically require a browser to load custom HTML pages from a network controller, in which custom HTML pages are specifically crafted to request specific information from the user. This feedback from the operator is then processed by internal firmware on the network controller to perform some specific action.

The demonstrated BMS architecture completely eliminates the need for network controllers or any custom firmware to process operator input. Instead, gateway devices serve up a HTML5 interface to the operator's browser, together with a complete Halo/S kernel coded in JavaScript. The user's browser then uses Asynchronous JavaScript and XML (AJAX) to directly communicate through the gateway using Halo/S bytecode. This allows the operator's browser to become yet another peer on a Halo/S network, and is able to communicate directly with Halo/S devices on the network without any intermediaries. This approach provides several large advantages over the traditional method:

- No "network controllers" are needed to process user commands, eliminating the need for this component
- System functionality is not limited to the specific HTML and firmware in the network controller, as direct Halo/S communication can be established with any device allowing unlimited flexibility
- Low-level network communication is drastically simplified; all devices only need to route Halo/S bytecode packets to handle everything from complete control algorithm changes to firmware updates

The browser software is organized into "widgets", each of which handles a portion of the overall software functionality:

- ServerManager**:** manage user authorizations, server management, data backups, and other required system administration functionality
- SetupDevices**:** used to set up devices and configure them into a network. This widget includes all security setup, firmware management, and other low-level tasks needed on the device level
- DataRecorder**:** used for data logging setup, data charting, and data exporting
- SystemModeler: graphically create the building layout to help visualize equipment during control commissioning
- SystemController**:** the HVAC/lighting control setup software, typically used by the installer and operations personnel
- SystemAnalyzer**:** provides a high-level dashboard for building tenants or other "casual" users to access data from the BMS and perform high-level analysis on the information
- SoftwareDeveloper**:** utilized by the installing contractor for creating customized control algorithms and making them available for installation using SystemController

2.2 TECHNOLOGY DEVELOPMENT

Significant development and modifications to the core technology were necessary during the course of the demonstration. These changes were either in response to discovered deficiencies in the product for the DoD environment, or for requested feature additions to make the platform more viable for adoption by various stakeholders.

Core Platform Usability Improvements and Bug Fixes

Although Paragon's Halo/S platform was TRL 7 at the time of installation, a host of bugs and usability deficiencies were discovered early on. In particular, several large changes to the setup and installation tools were made early on to facilitate the roll-out of the 349 sensors for the demonstration.

Many bugs were also uncovered in the core platform during the installation of the controls, requiring significant development and recommissioning to address the issues.

Wireless Range Improvements

After testing the wireless performance of the baseline sensors on the initial installation at Tinker, we discovered several scenarios where the wireless range was insufficient. For example, many of the test site buildings were built with extremely thick exterior walls. When placing sensors inside the metal enclosures of outdoor A/C condenser units, we were unable to get adequate wireless reception to gateways placed far inside the building.

To address this issue, an improved wireless module version was developed to provide increased wireless efficiency as well as enabling a gateway with an external antenna (see Figure 7) to increase the overall wireless link budget by +18dBm.

Figure 7. Gateway with External Antenna

Battery Life Improvements

Some significant battery life concerns were also discovered on certain site buildings which contained sensors on the fringes of the wireless range. These out-of-range sensors continuously sent wireless transmissions to the gateway, attempting to reconnect. However, every sensor communicating with the gateway would need to briefly wake up to confirm these messages were not intended for it, substantially shortening the battery life for all connected sensors in the building.

To improve this situation, we added in a wireless "backoff" algorithm in all devices. Each time a sensor lost connection to a gateway, it would increase a backoff time internally, delaying its reconnection to the gateway each time. This delay was able to substantially improve the battery life for the entire sensor network.

Sensor Mounting System

Early in the initial sensor installation phase, we discovered a wide variety of attachment surfaces existed at the installation site. In particular, our adhesive attachment method did not reliably hold the sensors on some interior wall surfaces (e.g., masonry), and also occasionally caused minor damage to the wall when removing the sensors.

To address this concern, a new 2-piece 3D-printed wall mounting structure was designed to provide a secure and more attractive solution. This new mounting system was utilized for the subsequent phases of the demonstration, providing a much improved experience.

ATO Architecture Requirements

Even though the core architectural design of the Halo/S platform is extremely secure, the full ATO certification process exposed many supervisory software functions which needed to be added. For example, the ATO requires the entire sensor/control system to perform daily backups of all settings and data for several years in fireproof storage. New supervisory software functionality had to be developed throughout the course of the demonstration to fully meet these requirements.

Additional Software Tools/Packages

In addition to the extra software functionality required by the ATO process, we realized that several other software pieces were needed to truly make the control platform marketable for performance contracts at DoD installations. Two of the key additional software packages which were developed are described briefly below.

- MeterManager: As part of our work with Tinker on baseline activities with their fence-to-fence ESPC, there was a significant need for a meter data management software (MDMS) to consolidate metering data at the base and assist in generating baselines.
- BACnetDiscover: In order to streamline the interface of our control system with existing 3rd party equipment, additional BACnet software tools were needed to improve usability and flexibility in dealing with a variety of existing equipment.

2.3 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

The wireless BMS platform is fundamentally very different from competing systems, and has significant advantages as well as limitations.

Advantages

- Cost: The Halo/S BMS has a 30% to 80% installed cost reduction over competing systems with an equivalent energy savings potential. The majority of this savings comes from a reduction in installation time due to the reduction in wiring installation, as well as the reduced engineering time to integrate and commission the system. Hardware costs of our wireless BMS are roughly 70% of competing systems as well, with savings coming from using common components across the product line to greatly reduce the total number of devices needed to meet the market requirements.
- Performance: Compared to competing BMS installations with an equivalent quantity of sensor/control points, the demonstrated BMS is roughly equivalent in terms of energy savings performance. However, the low cost of additional hardware can optionally allow for improved energy efficiency through increased system complexity.

Limitations

- Vendor Lock-in: The most significant barrier to adoption is vendor lock-in. Many DoD installations have attempted to unify their BMS systems to a single manufacturer (e.g., Johnson Controls, Honeywell, etc.), and it is quite difficult to convince those facility managers to incorporate other systems. However, even during the 3 years for this demonstration, there was a noticeable movement toward more open control architectures such as Niagara. By supporting common open protocols such as BACnet, we intend to allow full integration with Niagara and most other BMS systems. Customer mind-set continues to slowly migrate to a more open approach to BMS protocols, so this barrier to adoption should disappear with time.
- Education/Training: The other primary barrier is due to the significant technology change between competing hard-wired systems and the Halo/S system. For example, most controls contractors have limited or no experience with installation of wireless hardware. Procedures such as establishing wireless range inside a building and developing location strategies to work around building interference are foreign to most installers. Significant resources have been invested into education, marketing, and training for the involved stakeholders.

3 PERFORMANCE OBJECTIVES

The primary objective of this demonstration was to prove the viability of replacing existing BMS systems based on cost-savings alone. Most of the current DoD energy efficiency retrofit projects utilize performance contracts (typically ESPCs or UESCs). Marketing a technology for performance contracting involves two distinct customers: the DoD and the ESCO. Both must be enticed to utilize the product on new projects and bring about the large scale adaption of this technology at DoD facilities. Each of the four primary objective areas are detailed below, along with the customer for which each area pertains.

- Energy and Utility Savings (both DoD and ESCO): The most fundamental goal of the wireless BMS technology is to reduce energy usage and costs. Using a BMS to implement night setback alone will typically yield a 15% energy savings[1]. The goal of this demonstration was target at least a 15% overall energy reduction compared to baseline.
- Payback Period (Primarily ESCO): In order to entice an ESCO to utilize a new technology in a traditional performance contract, a simple payback of 10 years is typically necessary to make it attractive. **The fundamental objective of this demonstration was to verify a simple payback of 10 years based on utility savings alone.**
- Security (DoD): Due to the advanced technologies used in this BMS system such as wireless and network-based communications, there are substantial security requirements. This demonstration aimed to meet and exceed all security requirements of the Air Force and DoD, while simultaneously providing substantial monitoring and control benefits. A full Site ATO was targeted for the demonstration.
- Operation and Maintenance (O&M) (Primarily ESCO): At most DoD facilities, O&M responsibilities are outsourced to a contractor. Due to the tight relationship between O&M activities and energy usage, many ESCOs are looking to include O&M services as part of the performance contract. This larger contract size can increase the available capital for new equipment at the start of the contract. Any tangible benefit the BMS can provide for O&M activities can directly impact the potential adoption for performance contracts.

3.1 SUMMARY OF PERFORMANCE OBJECTIVES

Table 1. Performance Objectives

Performance Objective	Metric	Data Requirements	Success Criteria	Results
Quantitative Performance Objectives				
Reduce Facility Energy Usage	Energy Intensity (kBTU/ft^2)	Meter readings of energy used by individual buildings; square footage of buildings using energy	15% overall reduction in usage compared to baseline	**30.8% energy intensity reduction** across all demonstration bldgs
Direct Greenhouse Gas (GHG) Emissions	Direct fossil fuel GHG emissions (metric tons)	Meter readings of energy used by individual buildings; square footage of buildings using energy	15% overall reduction in usage compared to baseline	**26.7% GHG emission reduction** across all demonstration bldgs

Table 1. Performance Objectives (Continued)

Performance Objective	Metric	Data Requirements	Success Criteria	Results
Quantitative Performance Objectives				
Utility savings / installation cost	Simple payback (years)	Energy cost and total estimated installation cost for equipment by experienced contractor	<= 10 year simple payback	**4.8 year simple payback** average across all demonstration bldgs
Demonstrate high-level security and flexibility to adapt to installation reqt	Acquire full Site Authorization to Operate (ATO) from AFCEC for system	N/A	Acquire Site ATO	**Acquired Site ATO** in May/2017
Qualitative Performance Objectives				
Demonstrate BMS architecture functions properly	Interviews with demonstration system users to assess satisfaction of BMS operation; successfully control equipment	Interviews of demonstration system users, system check-outs after installation of BMS	Users stating their satisfaction with the BMS operation, including wireless communication robustness	**BMS functions properly**, and satisfied all users during demonstration
Demonstrate BMS M&V capabilities function properly	Power usage, temperature, humidity, light level, and occupancy	Data downloaded from BMS	Review data collected for reasonableness with expected operation of systems being monitored	**M&V capabilities function properly**, and satisfied all users during demonstration
Operation and maintenance (O&M) monitoring and diagnostics	Interviews with demonstration system users to assess perceived benefit degree of satisfaction by ESCO stakeholders	Interviews with demonstration system users	Users stating satisfaction with having remote monitoring capability and diagnostic tools. BMS successfully records data typically needed for M&V	**BMS successfully improves O&M efficiency**, and satisfied all users during demonstration
Ease of implementing programming upgrades	Interview users involved in controls upgrade to assess satisfaction	Interviews of controls contractor and engineers	Satisfaction of engineers and contractors with ease of installation of upgrade	**BMS control upgrade process is efficient**, and satisfied all users

3.2 PERFORMANCE OBJECTIVES DESCRIPTIONS

Facility Energy Usage

- Purpose: To show a reduction in energy usage in the demonstration buildings with full retrofit controls which is comparable to state-of-the-art competing BMS performance.
- Metric: A 15% building energy intensity reduction (kBTU/sqft) was targeted. This reduction is typical with state-of-the-art BMS retrofits on buildings with no existing "advanced" controls or setbacks enabled[1].

- Data: The site already has many per-building electricity and gas meters in place. These meters were manually read monthly during the demonstration. Based on the particular weather conditions during the demonstration, data was adjusted for climate using standard M&V methods. Additionally, building simulations were run to estimate energy usage during other seasons.
- Analytical Methodology: Energy usage was extrapolated for an entire calendar year for both baseline and the final control software installation. A comparison was then made based on these yearly totals.
- Success Criteria: At least 15% reduction in building energy usage was targeted.
- Results: **A 30.8% energy intensity reduction was achieved across all demonstration buildings.**

Greenhouse Gas Reduction

- Purpose: To show a reduction in greenhouse gas (GHG) output in the demonstration buildings with full retrofit controls which is comparable to state-of-the-art competing BMS performance.
- Metric: A 15% GHG reduction (metric tons) in overall building use was targeted. This reduction is typical with state-of-the-art BMS retrofits on buildings with no existing "advanced" controls or setbacks enabled[1].
- Data: The site already has many per-building electricity and gas meters in place. These meters were manually read monthly during the demonstration. Based on the particular weather conditions during the demonstration, data was adjusted for climate using standard M&V methods. Additionally, building simulations were run to estimate energy usage during other seasons.
- Analytical Methodology: Energy usage was extrapolated for an entire calendar year for both baseline and the final control software installation. The energy usage totals were used to calculate the reduction in GHG production from the baseline.
- Success Criteria: At least 15% reduction in GHG production was targeted.
- Results: **A 26.7% GHG emission reduction was achieved across all demonstration buildings.**

Payback Period

- Purpose: To show a simple payback period (utility savings / installed cost) which is attractive enough to allow installations using performance contracting alone.
- Metric: Simple payback (total installed cost / utility savings per year).

- Data: The overall site utility costs were calculated based on the site energy usage (see energy usage description above) along with the utility rates for the site. This amount was calculated for the baseline (pre-installation) period, as well as post-install condition, in order to calculate the utility cost savings. Additionally, the total installed cost of the project was be calculated as if installed by an experienced contractor using production equipment. The total cost of equipment and software was determined by Paragon. The installation labor was calculated based on detailed time studies during the demonstration period, and using industry standard contracting rates.
- Analytical Methodology: Average cost structure information was determined using on-site contractor rates, combined with past experience with controls installation projects in the Oklahoma region.
- Success Criteria: A simple payback of <10 years was targeted.
- Results: **A 4.8 year simple payback was achieved across the entire set of demonstration buildings.** At an individual building level, some buildings were not able to meet the 10 year goal, however these instances were either rare or were very close to meeting the target.

Security

- Purpose: To demonstrate best-in-class security for BMS systems; satisfy all security requirements related to wireless controls and facilitate installation at other USAF installations.
- Metric: Obtain a Site Authority to Operate (ATO) from USAF AFCEC at the end of the demonstration, allowing full implementation at Tinker AFB and fast-tracking approval at any other USAF facility.
- Data: Paragon worked extensively with AFCEC and the 38th CEIG (which is located at the installation site) to receive a Site ATO for the BMS. Once the ATO for the technology was issued, it can be used across other USAF facilities with minor approval needed for each new site.
- Analytical Methodology: The BMS was integrated into the Tinker CE-COINE network during the controls upgrade phase of the demonstration, and a remote access terminal was located at Tinker main base CE control.
- Success Criteria: Receive a Site ATO from USAF AFCEC.
- Results: **A Site ATO was successfully obtained in May/2017.**

Demonstrate BMS Functions Properly

- Purpose: To demonstrate the new BMS architecture is capable of reliably controlling the HVAC in the demonstration buildings.
- Metric: Subjective satisfaction of system users during demonstration.
- Data: Interviews with system users.

- Analytical Methodology: At the end of the demonstration, interviews were performed to establish the subjective performance of the BMS in controlling HVAC operation.
- Success Criteria: Satisfaction of system users with new BMS operation, including robustness of wireless communication and architecture in general.
- Results: **All users were satisfied the BMS functioned properly.**

Demonstrate BMS M&V Capabilities Function Properly

- Purpose: To provide best-in-class tools and information to the ESCO or O&M contractor for reduction in O&M cost and risk.
- Metric: Qualitative analysis of system performance during demonstration period.
- Data: Logged data from demonstration period.
- Analytical Methodology: M&V engineers analyzed the logged data from the demonstration and ensured it met the necessary criteria to be used in option B or C.
- Success Criteria: Ensure captured data meets the necessary M&V criteria for options B and C.
- Results: **The BMS provided sufficient data quality to meet M&V requirements, and all users were satisfied with the BMS performance for M&V purposes.**

Operation and Maintenance (O&M) Monitoring and Prediction

- Purpose: To provide best-in-class tools and information to the ESCO or O&M contractor for reduction in O&M cost and risk.
- Metric: Subjective satisfaction improvement from base maintenance personnel. Manpower required for some typical maintenance calls or routine service.
- Data: Interviews with system users during the demonstration.
- Analytical Methodology: Interviews were performed to establish the subjective advantage of the wireless BMS over the baseline system with regards to reducing maintenance costs and alerting the ESCO to performance issues which would impact contract performance.
- Success Criteria: Improved satisfaction compared to the baseline system in the small building space.
- Results: **All users agreed the BMS reduced O&M costs slightly compared to the baseline control systems.** However, these savings are difficult to capture inside performance contracts, as O&M costs are not commonly captured by ESPCs.

Controls Enhancements

- Purpose: To demonstrate that significant BMS controls enhancements can be implemented easily with the demonstration system.
- Metric: Subjective satisfaction of controls contractor and energy engineers with the ease of implementing controls upgrades.

- Data: Interviews with system users during demonstration.
- Analytical Methodology: Interviews were performed to establish the subjective advantage of the wireless BMS over the baseline system with regards to cost-effectively implementing significant HVAC equipment or control methodology changes.
- Success Criteria: Improved satisfaction compared to the baseline system in the small building space.
- Results: **All users were satisfied with the control upgrade process, and agreed it provided benefits over competing systems.** Several potential improvements to the system were pointed out, and these have been a focus of development after the demonstration was completed.

4 FACILITY/SITE DESCRIPTION

The demonstration was located at the 38th CEIG area ("38th" or "38th area") of Tinker Air Force Base in Oklahoma City. The 38th area is physically separate from the main base, and houses the 38th Cyber Engineering group, which is responsible for network security and setup for all USAF operations.

4.1 FACILITY/SITE LOCATION AND OPERATIONS

The Air Force was contacted early on during the project proposal generation with regards to a search for a suitable site, and several interested USAF installations responded. Out of those interested installations, the 38th area of Tinker was selected for the demonstration site for the following reasons.

- Existing Building Inventory: The 38th is composed entirely of building less than 50,000 sqft in size, and thus was an ideal representation of the target building type for the BMS. Additionally, no existing "modern" HVAC controls were present on the 38th, and thus we could evaluate the wireless BMS technology on a large set of buildings (see Table 2).
- Cyber Security: The 38th area houses the 38th Cyber Engineering group, which manages network security for the entire Air Force. Their support for the demonstration has also been important in validating the security of the wireless BMS, and helping speed the security approval along through AFCEC.
- Other Selection Criteria: The receptiveness of both Tinker 72d CE and 38th CEIG group to this demonstration was also a key selection factor. Their assistance in facilitating this project cannot be understated.

Of the roughly 24 structures on the 38th, 16 were selected to be part of this demonstration (Table 2). Unoccupied or trivial structures (e.g., the guardhouse) were ignored for the demonstration, as they consumed little or no energy. The HVAC equipment on these 16 buildings was a mix of packaged units, rooftop units, and chiller/boiler/air handler combinations on the larger buildings. Many of the midsize buildings utilize smaller "residential-type" packaged units which are commonly daisy-chained together to meet the capacity requirements. This wide range of HVAC equipment was ideal in providing a good proving ground for the wireless BMS, and helped get performance data for almost every type of HVAC setup that exists in this target building sector.

- Key Operations: The 38th CEIG is the primary group located at the demonstration site. The 38th has a small team of coordinators which facilitated access to the site for this demonstration. The 38th area has several buildings operated by other groups on the campus (e.g., a radar tower operated by FAA), however these buildings were ignored for the demonstration for logistic issues.
- The 72nd CE group is ultimately responsible for all HVAC and lighting systems on Tinker, and is located on Tinker main base. The Tinker energy manager is also part of the 72nd CE group, and is the primary site coordinator for the demonstration.

Table 2. HVAC Inventory for Demonstration Building

Building	Date	Sq Ft	Function	Cooling System	Heating System	Air Handling System
4001	12/04/14	2195	Office	Roodtop DX/gas package unit	Roodtop DX/gas package unit	None
4004	12/04/14	5899	Office	Downstairs: 8 two-pipe fan coils with chiller, Upstairs: 8 DX/gas split systems	Downstairs: 8 two-pipe fan coils with boiler, Upstairs: 8 DX/gas split systems	None
4012	12/04/14	14028	Office	Air cooled chilled water generator Trane Intellipak Model GCAFC30EABA000… (208 V) 4 condenser fans.	Teledyne Laars gas HW boiler, 715,000 Btu/hr Input, 579,150 Btu/hr output. Max 240 F. HW pump 3 HP.	AHU-1 Trane Climate Changer Type M(10) multi-zone (3 zones). CHW and HW Coils. AHU-2 Thermal Model 1-3401 MLT 172H-ZD, multi-zone (4 zones), mech room as mixed air plenum. 7.5 HP supply fan.
4023	12/04/14	14028	Theater	Chiller	Steam boiler	AHU-1
4028	12/04/14	1870	Office	2 DX/gas package units	2 DX/gas package units	None
4029	12/03/14	19220	Office	Carrier Model 30RBA 07054-52, outdoor air-cooled, CHW generator (208V) w/ CHW Pump.	Teledyne Laars gas-fired HW boiler. Model HH0600. 600,000 Btu/hr Input / 486,000 Btuhr Output. 1 HP HW Pump	2 Multi-Zone Units. #1 (5-zones): Cmdr Office; CS Office: Rm 109/108; Rm 105; Rm 107. #2 (8 zones)
4032	12/04/14	1803	Servers and office	Two outdoor air-cooled condensers: Carrier Model 50TM 00A-A-501 (208 V) plus Carrier Model 500Z0 8500 (208 V). Both units cycled on durng tour 12/4 (mild day). Seem to be cooling-only. Office heat probably from rooftop unit.		Rooftop AHU, prob cooling and heating, but may be heating only. Notes say electric heat. Prob serves office space.
4048	12/04/14	2583	Showers	Trane air-cooled condenser Model TTA120 B300FA (10 Tons total) with two refrigerant circuits, single condenser fan.	See below. Also, DHW AO Smith Model BTR 199 118	2 / Trane XR80 gas-fired packaged furnaces w/ DX coils
4049	12/04/14	3800	Gym	Outdoor AHU Unit Packages: Air-cooled DX unit AAON Model RM 020-8-0-AA02-242, (20-Ton) Two compressors two condensers, w/ Gas-fired furnace. System off on day of visit. Also, AAON 4-Ton similar unit, turned off at disconnect.	See above	See above

Table 2. HVAC Inventory for Demonstration Building (Continued)

Building	Date	Sq Ft	Function	Cooling System	Heating System	Air Handling System
4057	Wed 12/3/2014	9898	Office	West Side: Trane RAUCC 20EBY 1300 (200 V 100 Amp) outdoor air-cooled DX serving indoor DX-to-CHW heat exchcanger. **East Side**: 2 Carrier Weathermaker outdoor air cooled DX, Model 48TCEA 08 A2A5AOAOAO. And Model 48TJE 008 - 511AA. with gas fired heaters.	West Side: Gas-fired HW boiler Ajax 150,000 Btu/hr Input, 120,000 Btu/hr Output. **East Side**: Gas fired furnaces 120,000 to 180,000 Btu/hr Input, 96,000 to 144,000 But/hr Output. 165 F max air temp.	West Side: Multi-Zone (5 zones) Rm 105; Conf Rm; Rm 106; Rm 107; Rm 108. w/ HW and CHW coils. **East Side:**3 zones: See 2 Carrier Weathermakers above; plus split condenser DX w/ indoor AHU and electric heat.
4064	12/03/14	50780	Office	2 / Trane air-cooled condensing units Model LAVC-23312M (460 V) plus 1 / Trane LAVC 23308 M, one unit running. CHW Chiller indoors Trane RTUD 150 F2C02 A101, multiple compressors. Cycled 3 times during visit. CHW Pumps P-2 and P-3 both running. [Old McQuay "Chiller #1" not running; appears abandoned]	Kewanee Boiler 950 MBH (cycled off during visit). Two HW pumps, one running during visit.	2 / VAV AHU w/ Yaskawa VFDs, one on each floor. Upstairs VFD hunting slightly between 32 - 40 Hz.
4068	12/03/14	1483	Legal Offices	Air-cooled DX Copeland G8C 13060 3AL (208V)	Gas-fired atmospheric furnace in AHU	York
4069	12/04/14	4704	Office	3 DX/gas package units	3 DX/gas package units	None
4077	12/03/14	2450	Document storage	None	Gas heat only	None
4078	12/03/14	2400	Document storage	None	Gas heat only	None
4079	12/03/14	3674	Office	2 DX/gas units	2 DX/gas units	None

- Location/Site Map: Figure 8 shows an aerial map of the 38th, as well as the layout for all wireless gateways for the demonstration. Building B4068 houses the supervisory PC controller, and served as operational headquarters for the demonstration.
- Other Concerns: Several of the buildings do not have LAN connections, and are outside the wireless range of nearby buildings. These buildings were connected to the BMS network using a medium range wireless link.

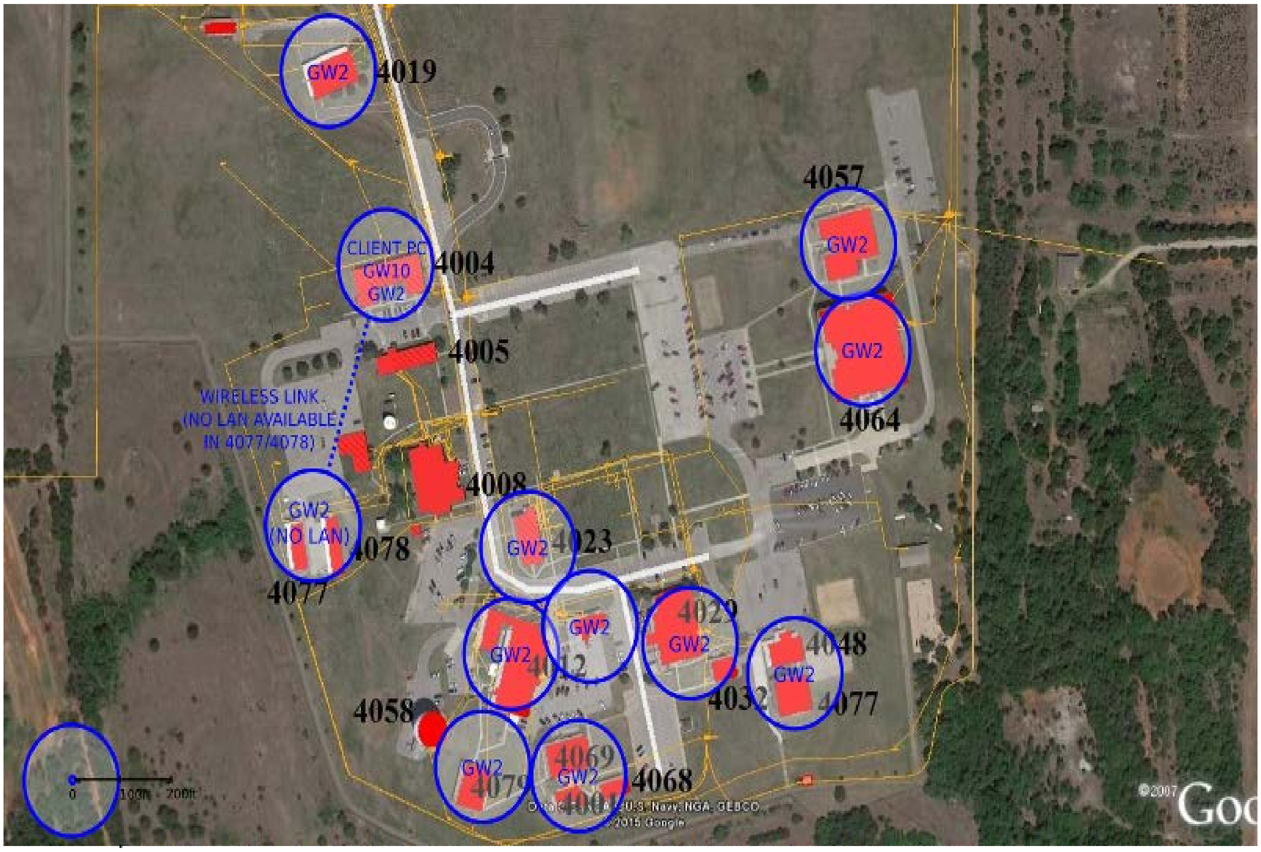

Figure 8. Aerial Map and Wireless Gateway Locations

4.2 FACILITY/SITE CONDITIONS

We experienced many changes in the site condition over the 3 year demonstration. Most buildings in the 38th campus are more than 40 years old and have aging HVAC systems. Furthermore, an extended labor strike with the O&M contracting company left many of the buildings with malfunctioning HVAC systems for almost 4 months during the key testing period for the demonstration. Although we hoped to collect at least a year's worth of data for many of the buildings with retrofit controls, the data collection period had to be shortened in many cases due to HVAC malfunctions and system replacements.

Several of the test buildings also had substantial mission changes, with 4 of the buildings becoming unoccupied for extended amounts of time. With one building in particular (B4079), the building was vacated immediately after we retrofit the controls and we were never able to collect performance data as a result of the HVAC systems being shut down. The effects of these unplanned changes are described in Section 8.1.

4.3 SITE-RELATED PERMITS AND REGULATIONS

- <u>Government Regulations</u>: All BMS equipment for this demonstration has received FCC approval. No other federal regulations are required for this type of equipment.

- Military Requirements: For permanent ICS installations on USAF sites, an Authority to Operate (ATO) is required by Air Force Civil Engineering Center (AFCEC). Alternatively, an Interim Authority to Test (IATT) can be obtained for 1-2 year projects for temporary testing. Full ATO approval is then required by the time the IATT expires if the equipment is to remain installed. A full site ATO was successfully obtained for the wireless BMS in May/2017. Both the IATT and ATO involve a similar application package which is described below. Note that AFCEC still utilizes the older DIACAP process for risk evaluation, although this process will be migrating over to the newer RMF process in the future.
  - Information Assurance Manager (IAM) Appointment Letter: An IAM is required to supervise and approve all activities under the IATT. The IAM must be from CE and be located at the actual base. IAMs must pass significant USAF network security testing as well ("Security Plus"). 72d CE did not employ anyone who could meet the strict IAM requirements at the beginning of the demonstration, so approval was obtained from AFCEC to replace the IAM with a Point of Contact (Mr. Zach Bright) for the IATT. However, Ms. Barbara Kochis was hired shortly after this phase, and replaced Mr. Bright as the full IAM for the remainder of the project.
  - Hardware and Software List: A comprehensive list of all hardware, software, and firmware revisions for installed hardware must be maintained throughout the project life.
  - Topology Diagram: A diagram showing the interaction between all equipment types, as well as the respective network topology "levels" for each type of equipment must be submitted. Other information such as ports and protocols used is also included on the diagram.
  - Modified DIACAP Implementation Plan (MDIP): The MDIP is a base-wide document which is intended to cover all ICS equipment at the installation. The base CE group must modify any existing MDIP to include the demonstration equipment, and sign off on the revised document.
  - Authority to Scan: A document must be submitted to allow CE to periodically run security scans on any PCs or computers connected to the CE LAN. For this demonstration, the 38th group ran the security scan on the networked PC and submitted the output results to CE for approval.
  - System Security Plan (SSP): The SSP is the most complex part of the IATT application, and involves a lengthy description of all security-related aspects of the system. The SSP for this demonstration included a detailed explanation of all networking and encryption methods used on the Halo/S platform. The SSP includes explanations for meeting a myriad of DoD security requirements (e.g., screen locks on PCs, password change intervals, etc.). The SSP must be signed by base CE.
  - Disaster Recovery Plan (DRP): This document details the procedure for all data backups, as well as contingency and restore procedures in the case of catastrophic failures or disasters.

It is worth noting that the majority of the security concerns related to the IATT are only relevant to systems connecting to a network. Systems with no network interaction or dedicated network wiring are of less concern, but are increasingly being treated with the same risk assessment vigor using the new RMF process.

During the IATT phase, the demonstration utilized several methods to help mitigate risk when tying into the CE COINE. First, a separate VLAN was established at the switch level, effectively isolating all networked equipment for the demonstration. Additionally, all traffic over this VLAN was passed through a dedicated tunnel at the switch level, further reducing the security footprint. Once we obtained the site ATO in May/2017, the system was connected directly to the CE COINE network, and the separate VLAN was discarded.

We estimate our time invested in the ATO process in this demonstration approached 800-man hours. Approximately half of this time was directly related to the ATO process, with the remainder spent on design changes to meet the full ATO requirements. At a rate of $165/hr, we estimate approximately $125k should be budgeted by contractors to complete the full ATO process.

4.4 PROPERTY TRANSFER

Control of the demonstration BMS system was turned over to Tinker AFB in May 2018. Many thermostats were removed at the end of the demonstration due the maintenance logistics, as Tinker is awaiting the contract award for a fence-to-fence ESPC in Q4/2018. The intention is to replace the majority of the controls at Tinker with the Paragon wireless BMS system, including all of the buildings included in this demonstration. Paragon controls for both building B4068 and B4029 were transferred to Tinker.

5 TEST DESIGN

- Fundamental Problem: Create a wireless BMS which can generate sufficient energy savings to provide a <10-year simple payback in the small building sector (<50000 sqft).
- Demonstration Question: Validate the design, installation, and operational feasibility of the demonstrated BMS, and calculate the effective return on investment of the BMS at the demonstration buildings.

5.1 CONCEPTUAL TEST DESIGN

- Hypothesis: The demonstrated BMS will generate sufficient energy savings and reduction in installation costs to provide a <10-year simple payback across a typical campus of DoD installation buildings in the small building sector.
- Independent Variable: The control system used on the demonstration buildings were changed from the baseline controls to the new wireless BMS.
- Dependent Variable(s): The primary monitored variables were: a) utility savings, b) installed hardware cost, c) design and installation costs, d) satisfaction of control and M&V performance, and e) O&M stakeholder satisfaction.
- Controlled Variable(s): The building envelopes and HVAC equipment were constant throughout the demonstration, and weather effects were factored out of the end results using accepted M&V methods. Building mission and occupancy was monitored in the individual buildings, and corrections for any potential impact on energy costs during the demonstration was made.
- Test Design: Cost and utility savings are the primary metrics around which the test has been designed. Since hardware costs are easy to tally, the installation costs are the main unknown. The actual installation phases for the project were divided into 2 halves, with only the second half of the installation being monitored to establish the costs. To determine the building split between these halves, the buildings were divided into 3 size groups (large, medium, and small), and were randomly split within these groups. This allowed the first half of the installation to be used as a training portion for all involved, and produced cost analysis results which will represent the true cost of an experienced controls technician installing the BMS.

  The performance of the project was evaluated based on utility and metered data from the baseline period. In addition, subjective criteria such as O&M benefits were determined through interviews with base facilities personnel.
- Test Phases: The project included the following phases:
  - Pre-test preparation and certification (IATT, demonstration plan, safety plan, contractor personnel registration, etc.)
  - Metering/monitoring equipment installation
  - Baseline data collection
  - Design of BMS system

– Controls installation part 1
– Controls installation part 2 (measure actual installation costs for this phase)
– Data collection part 1
– Controls software upgrade
– Data collection part 2
– Final data analysis and reporting

5.2 BASELINE CHARACTERIZATION

Existing energy usage was the primary baseline data collected during the baseline phase. Most of the buildings on the 38th currently have electrical meters located on the 480V stepdown transformers for each building. Manual gas meters are also present on most buildings or groups of buildings on the 38th. All of these meters are currently read monthly by the Tinker utility management team, so all overall electricity and gas usage for each test building is potentially available. However, approximately 1/3 of the building meters at the 38th are broken or otherwise not able to provide usable data for the test (see Table 3). Current transformers (CTs) were installed on major HVAC equipment in many demonstration buildings to quantify energy usage which was not properly captured by the utility meters.

Table 3. Valid Baseline Building Meters

Meter ID	Building	Meter Type
E1053	4001	Electricity
E0799	4002	Electricity
G1462	4004	Gas
E0079	4012	Electricity
G0080	4012	Gas
G1446	4028	Gas
E0337	4029	Electricity
E0703	4045	Gas
E0692	4048	Electricity
G0691	4048	Gas
E0335	4057	Electricity
G0334	4057	Gas
E1473	4058	Electricity
E0555	4064	Electricity
E0273	4068	Electricity
G0274	4068	Gas
E0705	4077	Electricity
G0704	4077	Gas

- Reference Conditions: The primary monitored parameters will be electricity use per building and major pieces of HVAC equipment, gas use per building, and indoor temperature/humidity.
- Baseline Collection Period: Electricity and gas usage for most the meters was available for at least 12 months prior to the demonstration, and throughout the demonstration period.
- Baseline Estimation: For buildings without valid utility meter data, we estimated baseline building usage using an estimated Energy Usage Intensity (EUI) value from comparable building types at Tinker.
- Data Collection Equipment: Existing "manual read" analog electricity and gas meters were utilized for the utility meter data collection. A 72d CE employee with the utility management group reads all meters on base each month and enters this data into their on-site meter data system. Data was exported from this database for our demonstration purposes.

Comfort levels and key equipment performance were also measured during the baseline phase to understand the current occupied space conditions and HVAC equipment performance to compare with the retrofit BMS system. We installed a total of 370 devices across the 38th area to capture this data (see Table 4).

Table 4. Installed Paragon Baseline Sensors

Building	**Usage**	**Building Size (sqft)**	**GW3**	**SC12**	**SC13**	**SC50+ CO2**	**SC18+ CT100**	**SC31+ Probe**	**SC50**
			Gateway	*Ambient Temp+ Humid*	*Ambient Light*	*CO2*	*Power Monitor*	*Thermistor Temp*	*Motion*
4004	Energy HQ	5889	2	4	4	0	10	22	4
4012		14028	2	10	0	1	8	12	2
4023	Theater	14028	2	10	2	1	6	6	2
4028	No label on map	1870	1	2	1	0	4	4	1
4029		19220	2	13	0	1	8	12	2
4032	Server room	1803	1	2	0	0	6	12	2
4048	Shower	2583	0	2	1	0	6	4	1
4049	Gym	3800	1	3	2	0	4	4	2
4057	Secure enclave	9898	2	7	0	0	10	12	2
4064	Largest building	50780	4	34	0	1	12	12	2
4068	Legal	1483	1	1	1	0	2	2	1
4069		4704	1	4	1	0	6	6	1
4077	No LAN	2450	1	2	1	0	2	2	1
4078	No LAN	2400	0	2	1	0	2	2	1
4079		3674	1	3	1	0	4	4	1
Total			**21**	**99**	**15**	**4**	**90**	**116**	**25**

- Reference Conditions: Both the occupied spaces in the test buildings, as well as all relevant HVAC equipment parameters were monitored during the baseline period. Temperature, humidity, light level, and motion were monitored in the occupied spaces, while air temperatures, water temperatures, and equipment power usage were primarily measured on all HVAC equipment
- Baseline Collection Period: The baseline period covered 12 months, however some of the collected data was not properly collected during the entire timespan due to various issues at the test site.
- Baseline Estimation: The collected baseline performance data was generally sufficient to understand the existing state of the equipment and performance. Thermodynamic simulations were done on a few systems to fill in some missing data. We utilized Paragon's SystemSimulator software for this modeling and simulation.
- Data Collection Equipment: Many types of Paragon sensors were used to provide baseline comfort and performance data, including ambient temperature and humidity (SC12), light levels (SC13), motion (SC50), air handler air temperatures (SC31), HW and CHW supply and return temperatures (SC31), and CO2 levels (SC75).

5.3 DESIGN AND LAYOUT OF SYSTEM COMPONENTS

The BMS consists of both monitoring and controlling equipment throughout the 16 demonstration buildings. The complete installation included 21 gateways, 349 sensors, and 24 control points in total, providing both performance monitoring and control capability for many of the HVAC systems.

System Design

Each building contains one or more Gateways, which are connected to the CE COINE network and create a local wireless network in the area. Surrounding sensors and controllers then connect to the gateway wirelessly. A single SuperGateway was installed in a central building (B4068) to serve as the main authentication and management node. The SuperGateway maintains constant communication with all Gateways, effectively creating a single connected network for any device to communicate with any other node on the network (see Figure 9). An Air Force PC workstation was also located in B4068, loading the interactive web software directly from the SuperGateway.

Components of the System

The demonstration included 6 types of components:

- Client PC/Station: A standard Air Force imaged Windows PC is located in building B4068 and provides all user access to the Halo/S system. This client PC loads all the web-based software directly from the SuperGateway using the Google Chrome browser (which is pre-approved for use on USAF systems, although not installed by default).
- SuperGateway: Physically located next to the client PC, and maintains communication with all Gateways on-site. It also stores all high-level system settings, and serves all the web-based software to the client PC.

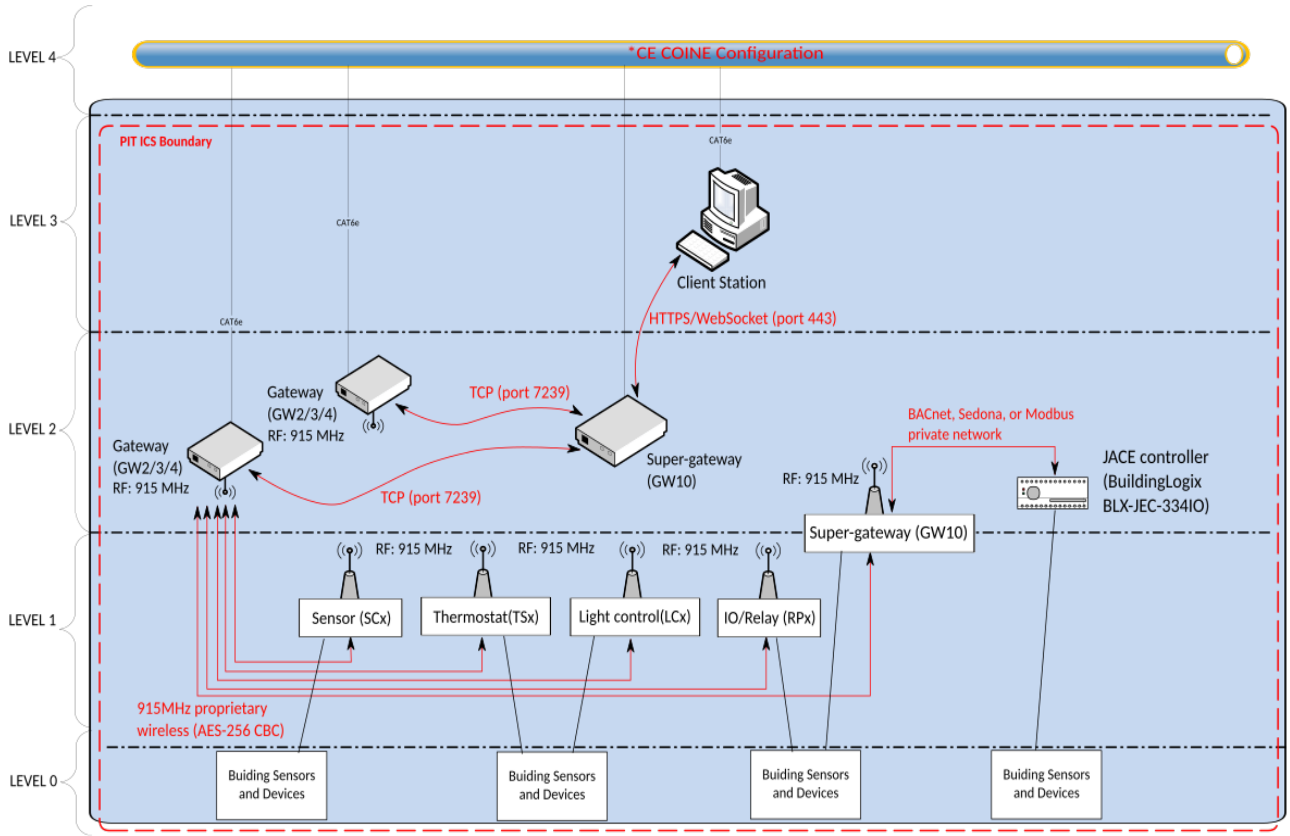

Figure 9. Network Topology

- A second SuperGateway was also utilized in the demonstration to interface with on-site Bacnet/IP hardware in B4029 (see 3rd Party Controllers section below). This second unit was configured to act as a wireless bridge, relaying information from an isolated Bacnet/IP network through a wireless link back to the building gateway. This allowed complete integration of Bacnet/IP networks on other equipment, allowing secure isolation from the CE COINE network.
- Gateway: Each building contains one or more basic gateways. These gateways marshal all wireless traffic, store sensor data, and act as a gateway between the wireless devices and the super-gateway via the CE COINE.
- Sensors (SCx): Over 12 different types of sensors were installed, ranging from temperature, humidity, power, motion, light, and other types of measurements.
- Thermostat (TSx): Thermostats were installed in the occupied spaces to monitor temperature, provide occupant input, and control HVAC equipment.
- 3rd Party Controllers: Niagara-based, 3rd party controllers were utilized for low-level air handler, boiler, and chiller controls. A second SuperGateway was connected to these controllers to provide high-level control and wireless connectivity.

Sensor/Baseline Methodology

The baseline sensor layout was organized into the following groups:

- Occupied Space Conditions: Temperature, humidity, motion (only in smaller buildings), ambient light (only in buildings with light harvesting potential), and CO2 (only specific buildings) were monitored in almost every building.
- Thermostatic Controlled Pkg Units: Air temperature probes were inserted into both the supply and return air ducts. CTs were also placed on many of the blowers to capture the blower power usage.
- Air Handlers: Air temperature probes were inserted into all zone supply air ducts, the return air duct, and mixed air chamber. CHW and HW temperatures were monitored to and from the air handlers, and blower motor power was measured with CTs.
- Chillers/Boilers: CHW and HW temperatures were monitored to and from the equipment. CTs were placed on many chiller motors to measure usage.

Control Methodology

The control architecture varies for each building, and depends on the HVAC equipment in use. Figure 10 shows a general small building control system for demonstration buildings with package DX/gas units or RTUs.

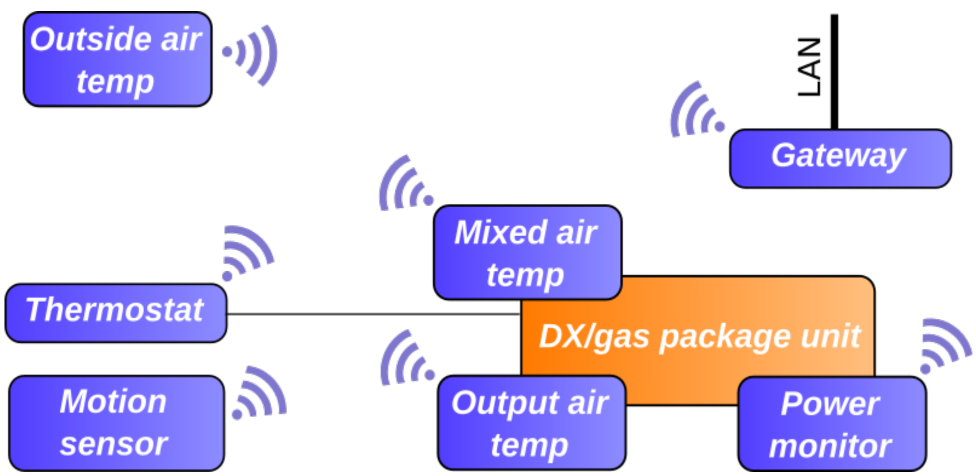

Figure 10. Small Building Control Example

The controls topology used on B4029, a larger building, is show in Figure 11 below.

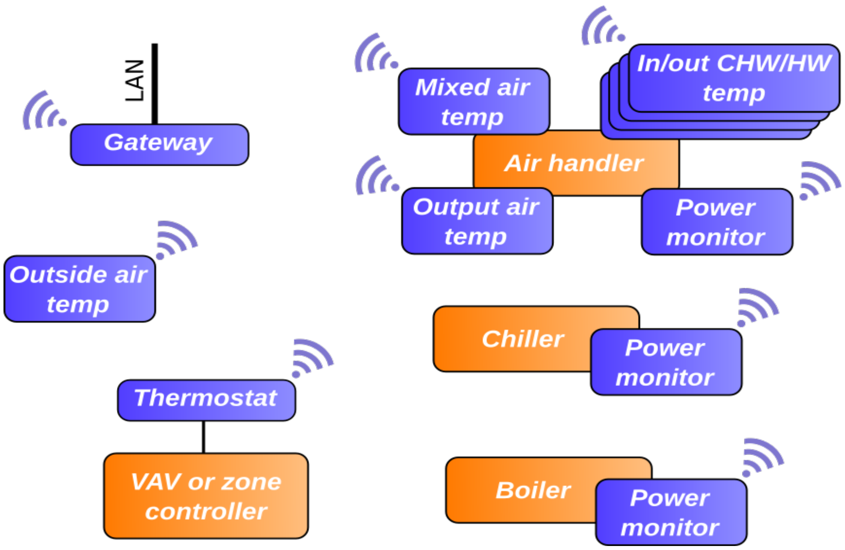

Figure 11. Large Building Control Example

Table 5 shows the summary of controls installed as part of this demonstration.

Table 5. Summary of Retrofit HVAC Controls

Building	Usage	Building Size (sqft)	TSx *Thermostat*	JACE *3rd Party JACE Controller*	GW10 *Super-gateway*	Notes
4001	Office	2195	0	0	0	Controls not retrofit due to additional hardware required
4004	Office	5889	8	0	0	Replace all upstairs units
4012	Office	14028	1	0	0	Replaced only thermostat
4023	Theater	3687	0	0	0	Controls not retrofit due to additional hardware required
4028	Office	1870	2	0	0	Replaced both thermostats
4029	Office	19220	0	4	1	Replaced all chiller, boiler and 2x AHU controllers
4032	Server room	1803	1	0	0	Only replaced thermostat in unsecured side of building
4048	Shower	2583	1	0	0	Replaced all thermostats
4049	Gym	3800	1	0	0	Replaced all thermostats
4057	Office	9898	0	0	0	Controls not retrofit due to additional hardware required
4064	Office	50780	0	0	0	Controls not retrofit due to additional hardware required
4068	Office	1483	1	0	0	Replaced all thermostats
4069	Office	4704	3	0	0	Replaced all thermostats
4077	Warehouse	2450	0	0	0	Cost/benefit was not high enough to replace
4078	Warehouse	2400	0	0	0	Cost/benefit was not high enough to replace
4079	Office	3674	2	0	0	Replaced all thermostats
Total			**20**	**4**	**1**	**0**

5.4 OPERATIONAL TESTING

The installation phases of the project were designed to provide both accurate performance data as well as accurate time/cost data for all installations. As the key objective of the demonstration was to understand the payback period for the technology, both of these areas were critical. The project installation was split into the following sections:

- Baseline Metering Installation (first 8 buildings): The first half of the buildings were inventoried, metering points selected, and equipment was installed (see Figures 12, 13, 14, and 15 for examples of installations). Installation time was not tracked, as this first batch of buildings were used for training and optimizing the installation procedure. As we were still waiting for the IATT approval needed to connect to the CE COINE, all data was stored locally on the gateways and was routinely downloaded every few months.

Figure 12. Occupied Space Tempature Sensor

Figure 13. Water Temperature Sensors

Figure 14. Chiller Power Measurement

Figure 15. Air Handler Temperature Sensor

- Platform, Hardware, and Software Fixes: Based on feedback from the initial baseline installation phase, significant upgrades were made to the overall platform and systems to improve performance and speed up installation.

- Baseline Metering Installation (last 9 buildings): With the fixes in place, the remainder of the sensors were installed while carefully tracking all design and installation time.
- Network Connection: Once the IATT was obtained, all gateways were connected to the CE COINE network, and the workstation PC was set up and configured to centrally manage the entire system.
- Thermostat Control Installation Part 1 (B4004): As with the metering phases, the controls installation phases were also separated to allow fixes and improvements to be utilized for later phases. 3 thermostats in B4004 were initially retrofitted to complete part 1.
- Thermostat Control Installation Part 2 (B4004, B4068, B4032, B4001, B4032, B4048, B4079): After initial testing feedback and fixes, 17 additional thermostats were deployed across the smaller buildings. Installation time was carefully tracked during this phase.
- Controls Upgrade (B4068): The B4068 controls were upgraded to test the performance and cost associated with the upgrade. Total upgrade costs were calculated.
- AHU Control Installation Part 1 (B4029): A controls subcontractor was utilized to replace the aging AHU controls in B4029 with a 3rd party "micro-JACE" controllers (see Figure 16 for installation). The boiler, chiller, and two air handler controls were retrofits with the new controllers, and all broken sensors and actuators were repaired at the same time. No Paragon equipment was installed during this phase, and the controllers were merely left in a "dumb" operational mode to maintain comfort at a specified set point in all spaces.

Figure 16. Retrofit AHU Controls

- AHU Control Installation Part 2 (B4029): After collecting data from the B4029 retrofit for 3 months, the high-level Paragon SuperGateway controller was configured and connected to the micro-JACE controls to implement energy savings algorithms.

Energy usage was tracked throughout the entire demonstration through the baseline metering system. Some additional sensors were added during the controls phase to collect additional information or provide feedback to the control algorithms.

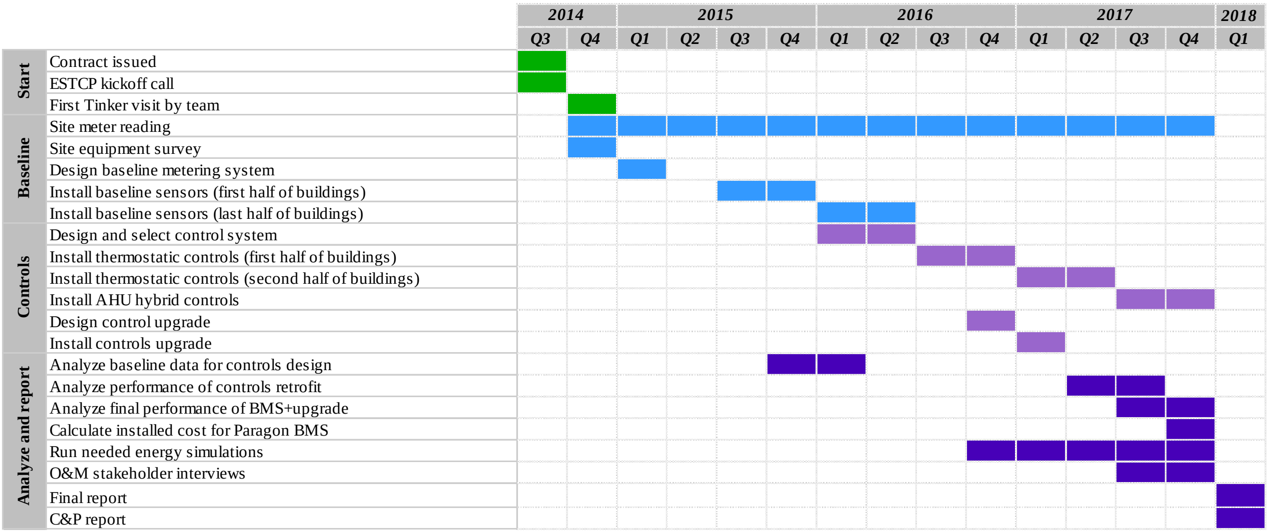

Figure 17. Demonstration Timeline

5.5 SAMPLING PROTOCOL

- Data Collectors: The full range of baseline collecting equipment is described in Section 5.2.
- Data Recording: Utility meter data was manually collected by 72d CE, and stored in their UMS utility database. All Paragon equipment stores data directly on the building Gateways. During the initial phase of the demonstration, an engineer visited each building monthly to download the data from each Gateway onto a laptop. Once the IATT was obtained, data was then collected via the workstation in B4068, with data backups being made to SD card.
- Survey Questionnaires: Many of the qualitative objectives required a survey questionnaire to be given to users of the demonstration system. We initially planned on getting significant feedback from Tinker personnel, however their contact with the demonstration system was limited and could not provide useful feedback. Instead, the controls installer and engineers directly involved with the BMS management were interviewed.
- Equipment Calibration: No field calibration was required during this demonstration. All equipment was calibrated during manufacture, and did not require recalibration during the period of the demonstration.
- Quality Assurance Sampling: Even though this demonstration collected data from a large number of sensors, all data measurement was fairly straightforward, and no single measured point was critical enough to necessitate redundancy or other countermeasures. CTs were used on all major HVAC equipment to help validate meter readings, and ensure the reasonableness of the collected data.
- Post-Processing Statistical Analysis: Graphical analysis methods were deemed sufficient to spot faulty data. Some simple engineering calculations were also be used to check the measurement of thermodynamic systems such as air handler heat transfer calculations.

6 RESULTS AND PERFORMANCE ASSESSMENT

6.1 BASELINE USAGE

The building meters from Table 3 were sampled by the 72d utility management team throughout the demonstration. These meter results were then used to run a temperature effect regression utilizing either cooling degree days (CDD) or heating degree days (HDD). If a suitable regression was found, we then adjusted the measured values to a typical meteorological year (TMY) data history, effectively removing any atypical climate effects from the yearly usage. Figure 18 shows an example regression run on an electric meter. In this example, a 75°F balance point gave the best regression fit and provided the fit equation shown.

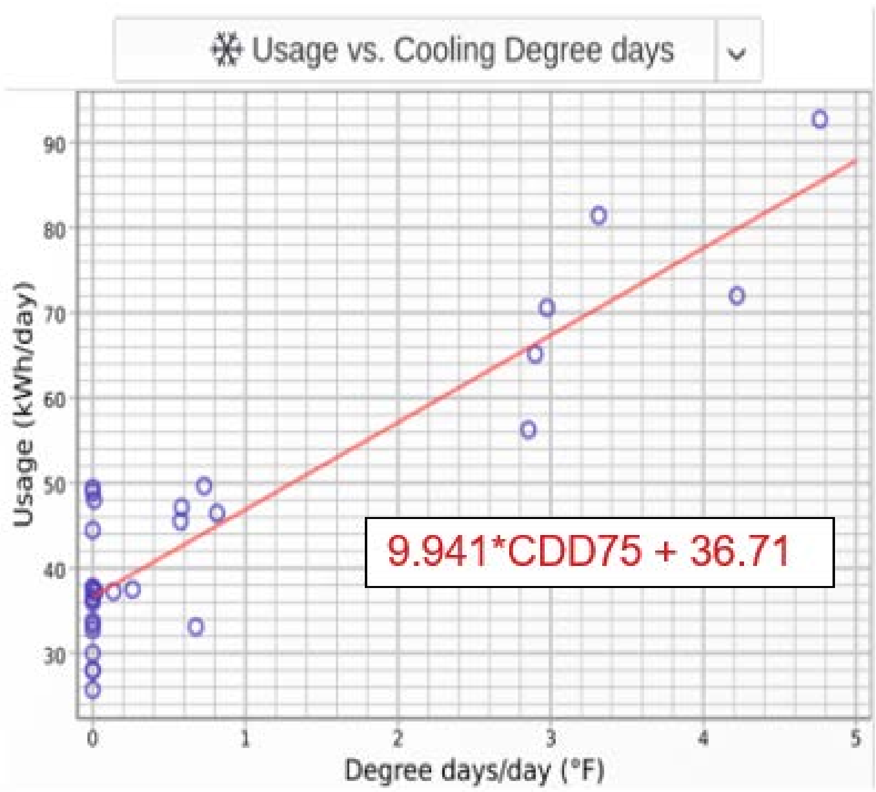

Figure 18. Example Temperature Regression

The actual TMY climate data (available on the NOAA website) was then applied to this regression equation, allowing us to calculate the meter usage for a TMY. A summary of all meter baselines is shown in Table 6.

Table 6. Temperature Normalized Yearly Usage for Valid Baseline Meters

Meter ID	Building	Meter Type	Normalized TMY Total	Units
E1053	4001	Electricity	63242	kWh
E0799	4002	Electricity	759102	kWh
G1462	4004	Gas	403691	ft^3
E0079	4012	Electricity	216278	kWh
G0080	4012	Gas	685515	ft^3
G1446	4028	Gas	96071	ft^3
E0337	4029	Electricity	548212	kWh
E0703	4045	Gas	18655	kWh
E0692	4048	Electricity	52883	kWh
G0691	4048	Gas	207059	ft^3
E0335	4057	Electricity	86412	kWh
G0334	4057	Gas	261475	ft^3
E1473	4058	Electricity	38110	kWh
E0555	4064	Electricity	653957	kWh
E0273	4068	Electricity	17426	kWh
G0274	4068	Gas	62242	ft^3
E0705	4077	Electricity	844	kWh
G0704	4077	Gas	224184	ft^3

Many of the 38th area buildings did not have valid utility meters in place. In order to calculate the estimated baseline usage for this building set, we calculated the energy unit intensity (EUI) of the metered buildings for each type of building usage, and multiplied it by the square footage of the unmetered buildings. The complete yearly usage data for the demonstration site buildings during the baseline period is shown in Tables 7 and 8 below. Overall electricity and gas utility costs are included based on a rate of $0.055/kWh and $0.49/therm.

Table 7. Baseline Electricity Usage for All Demonstration Buildings

Building	Sqft	Usage	Fuel Type	Source	Normalized TMY Total	EUI	Units	Yearly Cost
4001	2195	Office	Electricity	E1053	63242	98	kWh	$3,478.33
4004	11798	Office	Electricity	EUI est	212364	61	kWh	$11,680.02
4012	14028	Office	Electricity	E0079	216278	53	kWh	$11,895.31
4023	3687	Office	Electricity	EUI est	66366	61	kWh	$3,650.13
4028	1870	Office	Electricity	EUI est	33660	61	kWh	$1,851.30
4029	19220	Office	Electricity	E0337	548212	97	kWh	$30,151.66
4032	1803	Office	Electricity	EUI est	32454	61	kWh	$1,784.97
4048	2583	Shower	Electricity	E0692	52883	70	kWh	$2,908.56
4049	3731	Gym	Electricity	EUI est	67158	61	kWh	$3,693.69
4057	9898	Office	Electricity	E0335	86412	30	kWh	$4,752.64
4064	50780	Office	Electricity	E0555	653957	44	kWh	$35,967.62
4068	1483	Office	Electricity	E0273	17426	40	kWh	$958.43
4069	4704	Office	Electricity	EUI est	84672	61	kWh	$4,656.96
4077	2450	Warehouse	Electricity	E0705	844	1	kWh	$46.42
4078	2428	Warehouse	Electricity	EUI est	844	1	kWh	$46.42
4079	3674	Office	Electricity	EUI est	66132	61	kWh	$3,637.26

Table 8. Baseline Gas Usage for All Demonstration Buildings

Building	Sqft	Usage	Fuel Type	Source	Normalized TMY Total	EUI	Units	Yearly Cost
4001	2195	Office	Gas	EUI est	89995	41	ft³	$456.02
4004	11798	Office	Gas	G1462	403691	34	ft³	$2,045.59
4012	14028	Office	Gas	G0080	685515	49	ft³	$3,473.66
4023	3687	Office	Gas	EUI est	151167	41	ft³	$766.00
4028	1870	Office	Gas	G1446	96071	51	ft³	$486.81
4029	19220	Office	Gas	EUI est	788020	41	ft³	$3,993.07
4032	1803	Office	Gas	EUI est	73923	41	ft³	$374.58
4048	2583	Shower	Gas	G0691	207059	80	ft³	$1,049.21
4049	3731	Gym	Gas	EUI est	152971	41	ft³	$775.14
4057	9898	Office	Gas	G0334	261475	26	ft³	$1,324.95
4064	50780	Office	Gas	EUI est	2081980	41	ft³	$10,549.85
4068	1483	Office	Gas	G0274	62242	42	ft³	$315.40
4069	4704	Office	Gas	EUI est	192864	41	ft³	$977.28
4077	2450	Warehouse	Gas	G0704	224184	92	ft³	$1,135.99
4078	2428	Warehouse	Gas	EUI est	223376	92	ft³	$1,131.89
4079	3674	Office	Gas	EUI est	150634	41	ft³	$763.30

6.2 BASELINE HVAC PERFORMANCE

A significant quantity of HVAC performance data was collected during the baseline period. Figure 19 shows the monitored data streams for building B4048, which is typical for the demonstration buildings. Sample measurement charts for all demonstration buildings is included in the Appendix.

Figure 19. Sample Measured Baseline Data forB4068

We analyzed the baseline data to evaluate 8 different performance areas:

- Night setback of the occupied space temperature setpoints
- Occupancy schedules, including "first person in" and "last person out" of a building during a typical day
- Lighting schedules, with particular interest in proper lighting shutoff during unoccupied periods
- Temperature and humidity stability in occupied spaces, including ability to meet requested setpoint and balancing between zones
- Proper economizer operation on AHUs
- Blower/Fan operation when not needed
- HW or CHW supply temperature "outside air reset" operation, indicating a variable supply temperature setpoint based on anticipated heating/cooling demand
- Existing enthalpy-adjusted controls, indicating humidity is factored in to HVAC control decisions

Figure 20 shows an example 24-hour period for B4048, a gymnasium building. Several key analysis points can be extracted from this data set:

1. Both inside temperature sensors track each other very closely (blue and maroon series), indicating the inside temperature balancing is good.
2. The inside temperature sensors indicate the HVAC setpoint range is between 68-70F through the entire period, with no night setback.
3. The building is unoccupied between 1730 to 0630 hours each night, suggesting a possible night setback schedule.
4. Many random lapses in temperature control occur, indicating problems with either the existing HVAC equipment or control

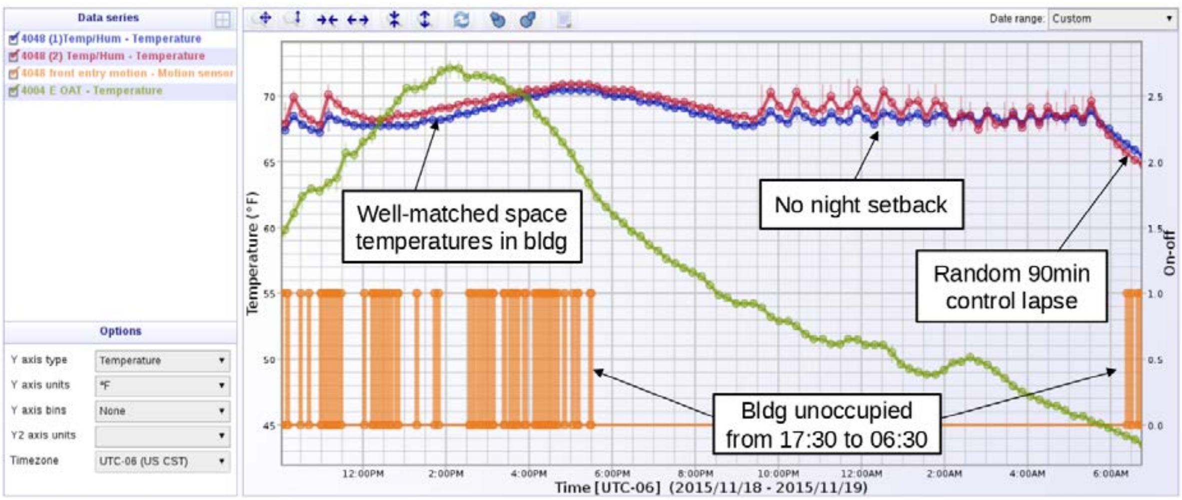

Figure 20. B4048 HVAC Performance Analysis

Performance data for B4064, which is a larger building containing AHUs, is charted in Figure 21. The following performance points can be made from the data:

1. The HW supply temperature does not vary at all, even when the outside air temperature warms sufficiently to eliminate the building heating load. This indicates there is no outside air temperature reset, which can provide key energy savings.
2. The AHU blower is on at all times, even during unoccupied periods with little heating or cooling demand.
3. No night setback is utilized for inside temperature setpoints.

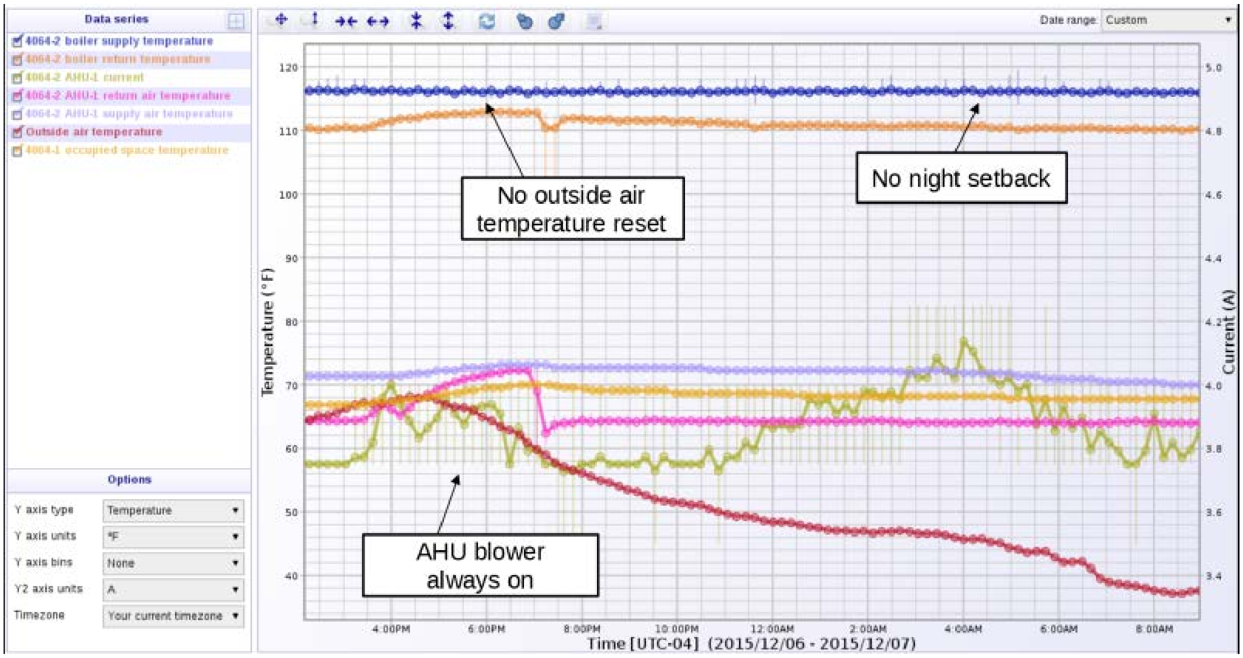

Figure 21. B4064 HVAC Performance Analysis

A summary of all performance findings is shown in Table 9. In general, no energy savings controls were present on any of the demonstration buildings. Building B4004 contained several thermostats with night setback programmed, although most of them were not utilizing this feature properly due to incorrect clock settings or user override settings.

Table 9. HVAC Performance Summary for Demonstration Buildings

Building	Usage	Occupied Schedule	Night Setback	Proper Lights Shutoff	Proper Space Conditions	Economizer Works	Proper Blower Shutdown	HW/CWH Temperature Reset	Enthalpy Optimization
4001	Office	M-F, 0530-1700	No	Yes	Yes	N/A	N/A	N/A	N/A
4004	Office	M-F, 0530-1700	Some	Yes	No	N/A	N/A	N/A	N/A
4012	Office	M-F, 0530-1700	No	Yes	Yes	No	No	No	No
4023	Office	M-F, 0530-1700	No	Yes	Yes	N/A	N/A	N/A	N/A
4028	Office	M-F, 0530-1700	No	Yes	Yes	N/A	N/A	N/A	N/A
4029	Office	M-F, 0530-1700	No	Yes	No	No	No	No	No
4032	Office	M-F, 0530-1700	No	Yes	Yes	N/A	N/A	N/A	N/A
4048	Shower	S-S, 0500-2100	No	Yes	Yes	N/A	N/A	N/A	N/A
4049	Gym	S-S, 0530-2100	No	Yes	Yes	N/A	N/A	N/A	N/A
4057	Office	M-F, 0530-1700	No	Yes	Yes	No	No	No	No
4064	Office	M-F, 0530-1700	No	Yes	Yes	No	No	No	No
4068	Office	M-F, 0530-1700	No	Yes	Yes	N/A	N/A	N/A	N/A
4069	Office	M-F, 0530-1700	No	Yes	Yes	N/A	N/A	N/A	N/A
4077	Warehouse	None	No	Yes	Yes	N/A	N/A	N/A	N/A
4078	Warehouse	None	No	Yes	Yes	N/A	N/A	N/A	N/A
4079	Office	M-F, 0530-1700	No	Yes	Yes	N/A	N/A	N/A	N/A

It is also worth noting that this type of performance analysis is required during the investment grade audit (IGA) phase of an ESPC. The quality of the collected baseline data using the wireless BMS equipment demonstrates the ability to meet the requirements for IGA data collection by an ESCO.

6.3 SIMULATION MODELING

Several of the demonstration buildings were not able to receive retrofit controls for various reasons. As such, we needed to utilize simulations to estimate the energy savings from various energy efficiency methods on these buildings. To do this, we utilized the actual measured baseline building conditions to tune a simulation model for each building at the site.

Figure 22 shows a sample time segment for B4068, showing a high resolution inside temperature profile (orange) compared to the outside air temperature (blue). Paragon's SystemSimulator software was used to build a simple thermodynamic envelope matching the overall floor area and condition of the demonstration building. HVAC sizes were also configured to match the known equipment in the building. The overall insulation quality, thermal mass, and HVAC performance parameters were then adjusted to produce a simulated result which closely matched the actual measured performance (see Figure 23). Once this match was achieved, the simulation model for the particular building was saved and utilized for later analysis.

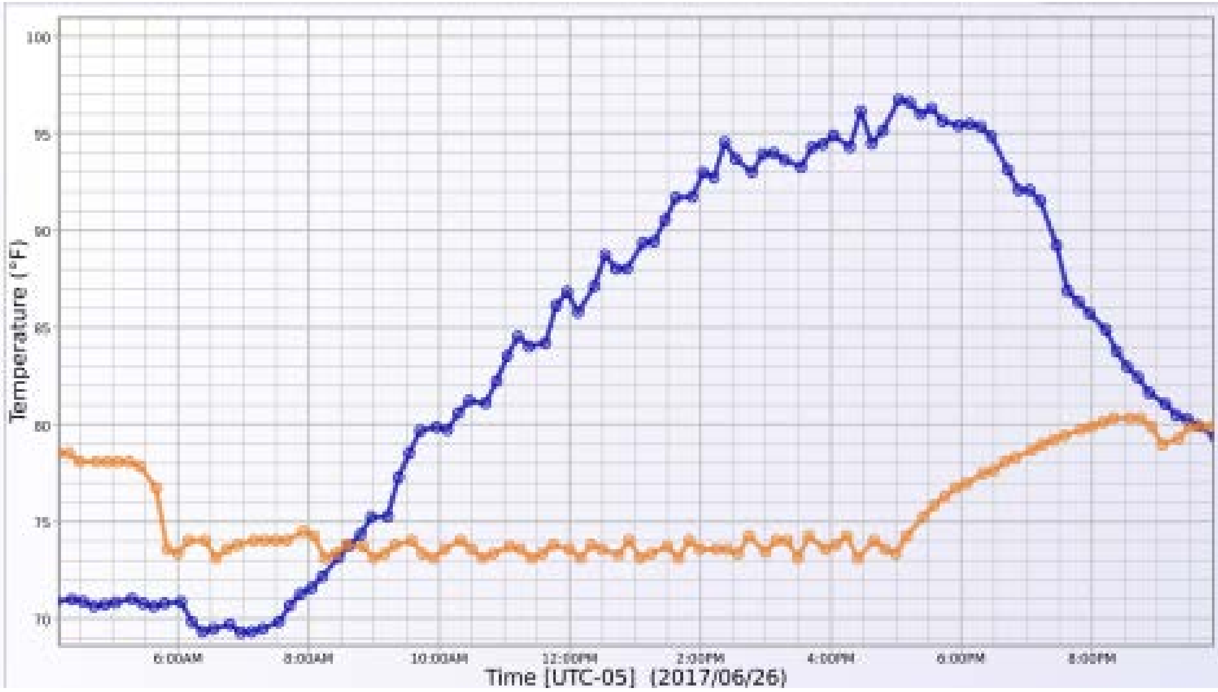

Figure 22. B4068 Actual HVAC Response

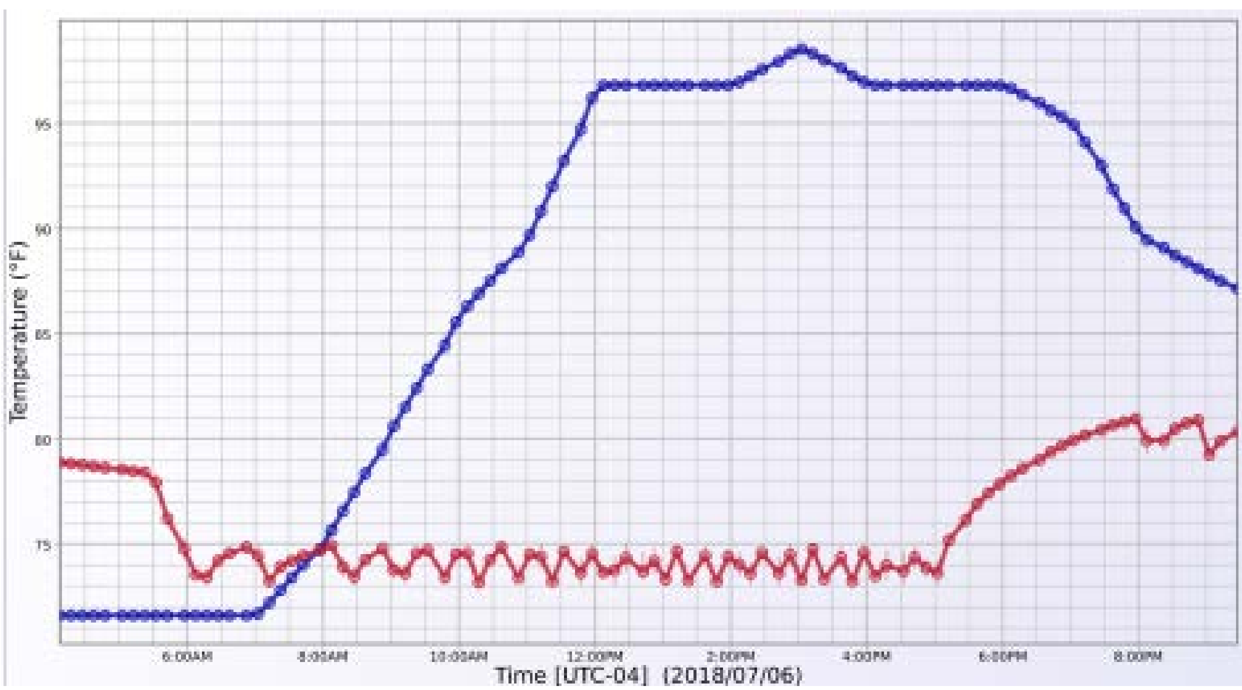

Figure 23. B4068 Simulated HVAC Response

Figure 24 shows an example model layout utilized for the simulations. Each building was fully modeled using existing floor plan drawings (orange), and overlaid on a satellite photo for display purposes.

Figure 24. Demonstration Building Set Modeling

6.4 THERMOSTAT CONTROLS

After retrofitting certain thermostatically controlled buildings, occupied space temperature and humidity were monitored to confirm the comfort targets were being met. Energy savings configurations such as night setback and humidity optimizations were also analyzed.

Figure 25 shows the post-retrofit performance for B4068. The blue series represents the outside air temperature (OAT), while the orange series shows the controlled inside temperature. The data demonstrates the night setback is operating properly at night between 1700 to 0530 each weekday, indicating proper operation.

We then analyzed the reduction in energy use after the thermostat retrofits. We utilized B4068 for this analysis primarily, as we had the most reliable metering data for this building as well as the best physical access to it. Electricity and gas usage was charted before and after the retrofit, and a temperature correlation regression was performed to account for climate effects (see Figure 26). A 26% overall building electricity savings and 49% overall building gas savings were achieved in B4068 with the wireless BMS.

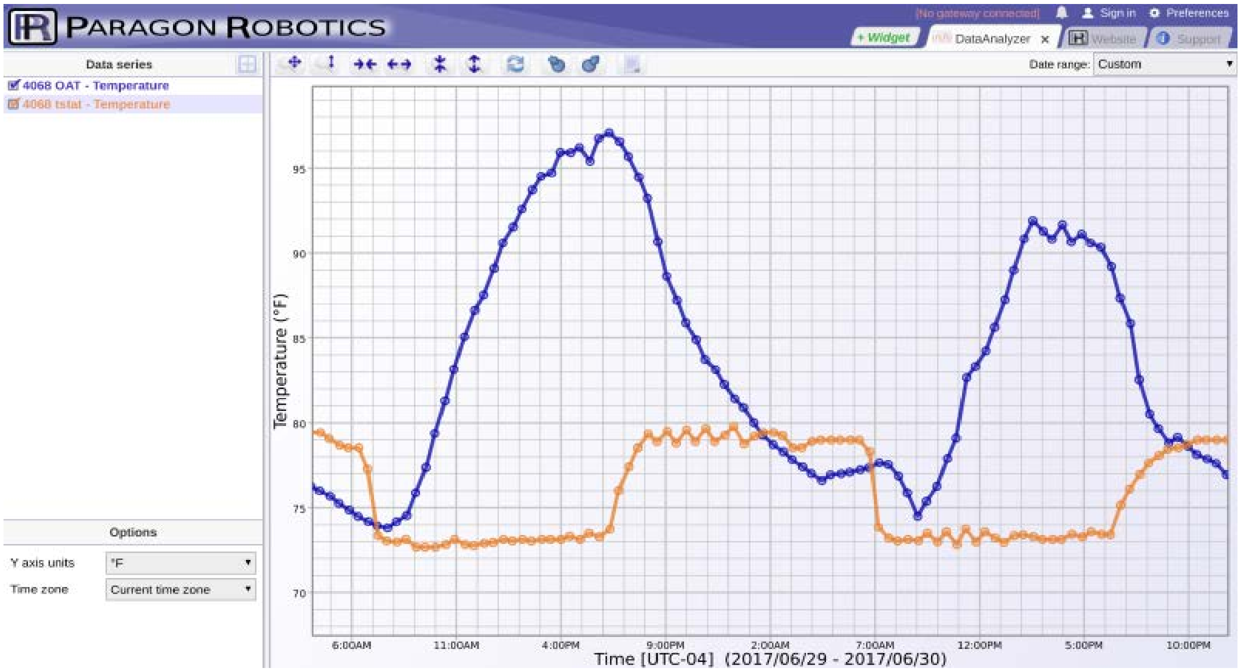

Figure 25. B4068 Post-retrofit HVAC Response

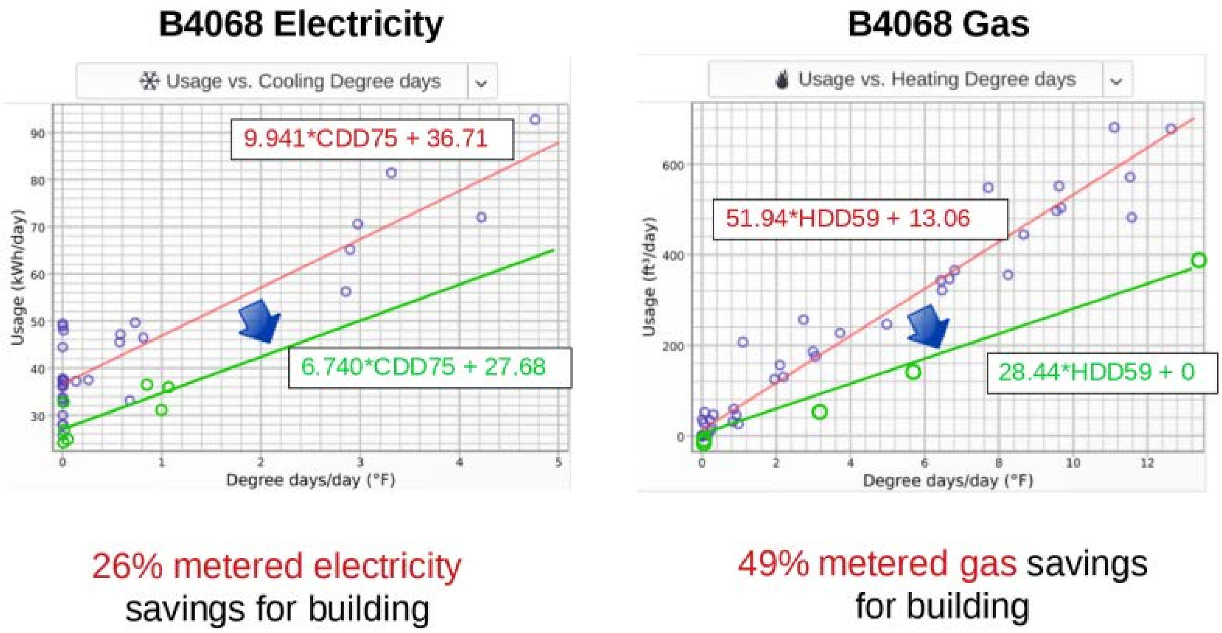

Figure 26. B4068 Utility Savings After Retrofit

A similar approach was used for all thermostatically controlled building within the demonstration area (see Table 10). 21.8% overall electricity savings and 39.4% gas savings were achieved across the entire thermostatically controlled building portfolio.

Table 10. Post-retrofit Savings on Buildings with Thermostatic HVAC Control

Building	Size (sqft)	Baseline Usage		Post-retrofit Usage		Utility Savings		GHG Savings
		Electricity (kWh)	Gas (cf)	Electricity (kWh)	Gas (cf)	Electricity (%)	Gas (%)	
B4001	2195	63242	89995	47103	46201	25.5%	48.7%	27.7%
B4004	11798	212364	403691	171920	220653	19.0%	45.3%	22.3%
B4023	3687	66366	151167	50097	78081	24.5%	48.3%	27.9%
B4028	1870	33660	96071	24996	49084	25.7%	48.9%	29.8%
B4032	1803	32454	73923	24086	37771	25.8%	48.9%	29.1%
B4048	2583	67158	207059	50195	106098	25.3%	48.8%	29.6%
B4049	3731	86412	152971	65254	79325	24.5%	48.1%	27.2%
B4057	9898	653957	261475	521035	170460	20.3%	34.8%	20.7%
B4068	1483	17426	62242	12895	31744	26.0%	49.0%	30.8%
B4069	4704	84672	192864	64496	100200	23.8%	48.0%	27.3%
B4077	2450	844	224184	844	195040	0.0%	13.0%	12.4%
B4078	2428	844	223376	844	194337	0.0%	13.0%	12.4%
B4079	3674	66132	150634	49915	77800	24.5%	48.4%	28.0%
Total	**52304**	**1385531**	**2289653**	**1083682**	**1386795**	**21.8%**	**39.4%**	**23.7%**

6.5 AHU CONTROLS

We first analyzed the control performance after the B4029 AHU controls were replaced with the micro-JACE controllers. At this stage, the micro-JACE controllers were only maintaining a constant comfort setpoint for all occupied spaces. Figure 27 shows temperature profiles for one of the 2 AHUs. The yellow series indicates the controlled hot deck air temperature, the blue series at the bottom of the chart indicates the cold deck air temperature, and all other series represent space temperatures. The chart shows good stability in the control of all these temperatures by the micro-JACE controllers.

Once the JACE controllers were confirmed to be properly maintaining comfort levels and following proper sequence of operations, we implemented our SuperGateway controller to implement the 8 different savings areas described in Section 6.2.

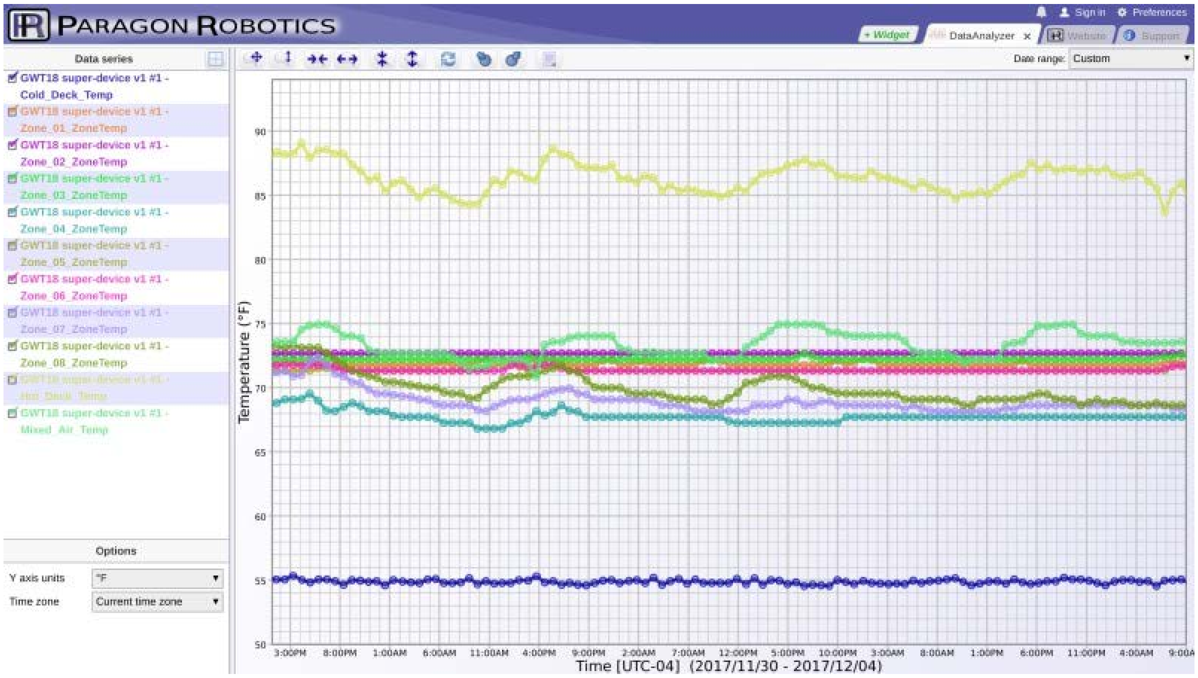

Figure 27. B4012 AHU Temperature Profiles with JACE Control (No Efficiency Algorithms)

Due to HVAC equipment outages, SuperGateway long-term stability issues, and lack of time before contract end, we were unable to collect enough performance data after the SuperGateway installation to confirm savings and performance on the actual installation. We instead evaluated the operation of the SuperGateway on a bench-test setup to confirm the energy savings algorithms behaved as expected. By confirming the SuperGateway properly controlled all simulated actuators in response to simulated inputs on the bench-test, we could then "manually" control the building HVAC equipment to replicate the SuperGateway control and measure the actual energy savings from the building. Simulations could also be done afterward using the theoretical SuperGateway algorithms. The estimated utility savings were then calculated using a similar simulation approach as described in Section 6.4.

Table 11 show a summary of the energy savings for all demonstration buildings containing AHUs. Across all demonstration buildings with AHU controls, both our measurements and simulations show an overall electricity savings of 27.2% and gas savings of 41.9%.

Table 11. Post-retrofit Savings on Buildings with Thermostatic HVAC Control

		Baseline Usage		Post-retrofit Usage		Utility Savings		
Building	**Size (sqft)**	**Electricity (kWh)**	**Gas (cf)**	**Electricity (kWh)**	**Gas (cf)**	**Electricity (%)**	**Gas (%)**	**GHG Savings**
B4012	14028	216278	685515	140581	294772	35.0%	57.0%	39.2%
B4029	19220	548212	788020	361820	354609	34.0%	55.0%	36.0%
B4064	50780	653957	2081980	529705	1415746	19.0%	32.0%	21.5%
Total	**84028**	**1418447**	**3555515**	**1032106**	**2065127**	**27.2%**	**41.9%**	**29.5%**

6.6 QUALITATIVE ANALYSIS

The qualitative objectives were evaluated as 4 separate categories. We initially intended to utilize questionnaires to evaluate several of the qualitative objectives with specific user groups. However, due to the actual execution of the demonstration, government personnel had very little interaction with the core functionality of the system.

The primary users of the system were Paragon engineers and a subcontractor controls technician. As these users would not have an unbiased opinion on the overall satisfaction of the system performance, we instead opted to interview these users to capture a list of what went well and what could be improved upon.

BMS Functionality

The BMS functionality was evaluated at the end of the demonstration period. Specifically, we wanted to ensure the BMS could fully meet the following performance areas:

- Proper Temperature Control of Occupied Space: The BMS accurately controlled space temperatures within the specified tolerance bands. Users did not observe any occurrences of control errors which were not attributable to other causes.
- Allows Tenant Interaction for Minor Temperature Adjustments: All thermostats were configured with user-editable programs to allow minor setpoint adjustments. There were some initial complaints from building tenants on the interface early in the demonstration, but these were addressed midway through the project through software changes.
- Allows Remote Viewing and Modification of Programming: All sensor and control points were accessible remotely, allowing remote troubleshooting and configuration of all performance parameters.
- Properly Executes Comfort Schedules: The BMS was able to properly execute all schedules. There were initial issues with auto changeover from heating to cooling seasons, but these were addressed midway through the project through software fixes.
- Interfaces with 3rd Party Control Systems**:** The BMS was able to read and write all points on the 3rd party micro-JACE AHU controllers via a BACnet/IP interface. Additional software tools were developed during the demonstration to further improve the BACnet/IP setup process.

Based on the performance areas described above, all stakeholder users of the demonstration system agreed the wireless BMS achieved the basic BMS functionality objective.

M&V Capability

To evaluate M&V capability, we focused on analyzing the following areas:

- All Typical Sensor Types are Available and can be Integrated: Ambient air temperature + humidity, duct air temperature, pipe (water) temperature, CO2, current transducer (CT) current, pulse-counting, light levels, and motion sensors are all provided directly by Paragon. Other sensors can be integrated into the M&V system via common interface standards such as 0-5V or 4-20mA.

- Usable Hardware and Software Installation Process: By the end of the demonstration, the installation process had been significantly matured, allowing a typical 10-minute installation time per sensor.
- Reliable Data Collection: After the initial usability and reliability fixes had been implemented, all users agreed the reliability of the system was sufficient for M&V purposes.
- Data Retrieval Process is Usable and Efficient: The data download process was determined to be efficient, allowing long-term M&V operations to minimize labor requirements.

Based on the performance areas described above, all stakeholder users of the demonstration system agreed the wireless BMS achieved the basic M&V functionality objective.

It is difficult to quantify the cost benefit of the M&V capabilities. For Option A or B, in our experience the cost of a yearly in-person visit assessment would be around $400 per 10,000 sqft building. Calculating a 10 year simple payback target, this M&V cost for competing systems would be around 8% of the total installed BMS cost for a building of this size.

O&M Benefits

The operations and maintenance benefit of the wireless BMS primarily depends on its ability to reduce the time needed to troubleshoot and repair problems that may occur during the system lifespan. The following performance categories were analyzed:

- Ability to Remotely Troubleshoot Basic HVAC Problems: The built-in M&V capabilities of the BMS provided sufficient data to remotely troubleshoot most HVAC problems that arose. Paragon was commonly requested to isolate building comfort issues during the demonstration to understand if HVAC equipment failures were the culprit, or if other control issues were affecting comfort.
- Reliability of Controls Hardware/Software System: After the initial usability and reliability fixes had been implemented, all users agreed the reliability of the system was sufficient for O&M purposes.

Several stakeholder asked us to try and quantify the actual O&M savings that were achievable with the wireless BMS compared to the baseline system. Any quantifiable O&M savings could potentially be used to provide additional yearly savings to improve return-on-investment. We estimate our wireless BMS would, in average, eliminate one "truck roll" every 2 years for a building. Depending on building size, this value could range from 6-20% of the installed BMS cost.

In practice, this methodology proved problematic for several reasons. Even though the wireless BMS can theoretically provide reduced O&M costs, these savings are not traditionally taken into account with common O&M cost calculation methodologies used by O&M service providers. Furthermore, many ESPCs do not allow O&M savings to be captured by the contract, as O&M is commonly handled by either 3rd party contractors or government personnel. These existing O&M agreements are typically not transferred, preventing an ESCO from easily capturing any savings during the ESPC contract performance period.

Ease of Control Upgrades

Most actual DoD installations are constantly in flux; missions are constantly changing and facilities are constantly being upgraded. To demonstrate the marketability of our BMS system for these real world applications, we intended to show how efficiently the BMS could handle system upgrades. Based on interviews with the Paragon and subcontractor users of the systems, the following areas summarized what went well:

- <u>Software Upgrades on Individual Hardware</u>: The actual software upgrade process on each individual piece of control hardware went smoothly. The process was done remotely, and took about 3 minutes per device.
- <u>Upgrade Capability was Expansive and Effective</u>: The upgraded software functionality was effective in improving energy efficiency, as well as accommodating changes to the underlying HVAC systems.

The following areas of the system performance could be further improved:

- <u>Upgrade Process for Large Control Groups could be Faster</u>: When upgrading large groups of equipment, the upgrade process was slow and required more manpower than originally anticipated. This efficiency can be improved through the high-level software interface, and development work has already begun to improve the key software pieces to streamline upgrades for large systems.
- <u>Documentation for Software Versions could be Improved</u>: Several users had concerns with the ability to track the actual algorithm upgrades when they are made. Again, this concern should be improved through the high-level software interface in the future.

All users agreed the upgrade process went well and achieved the goal of providing impressive control upgrade capability quickly and without hardware changes. Additional software development has already been completed after the demonstration period to address many of the shortcomings listed above.

7 COST ASSESSMENT

7.1 COST MODEL

The BMS life cycle cost savings were established over a 25 year life, and evaluated for savings using the parameters in Table 12 below. Of the life cycle cost parameters, the hardware costs, installation costs, and energy savings are the most significant factors in the life cycle calculation.

Table 12. Life Cycle Cost Parameters

Cost Element	Data Tracked During Demonstration
Hardware capital costs	As all Paragon hardware list prices were published prior to this report, we were able to simply use the list prices for all hardware.
Installation costs	Engineering, acquisition, installation, and commissioning time was tracked during the installation phase. Established labor rates were used to calculate actual installation costs.
Consumables	The primary consumable is the battery replacements for the wireless devices. Battery life was estimated based on performance during the demonstration.
Facility operation costs	Electricity and gas usage was determined using the methodology explained in Section 6.4
Maintenance	We attempted to estimate potential operating and maintenance (O&M) savings for the system based on subjective interviews with various stakeholders.
Hardware lifetime	A 25 year hardware lifetime was used for all calculations, and premature replacement costs were factored into the maintenance cost portion.
Operator training	The cost of operator training was included based on manpower estimations of other manufacturer's training recommendations.
Salvage value	The BMS was assumed to have no salvage value at end-of-life.

7.2 COST ANALYSIS AND COMPARISON

From a cost perspective, we needed to analyze the return on investment for the wireless BMS at a typical DoD facility. To understand this, we needed to calculate both the total installed cost for the system as well as the utility savings it generated. We performed separate cost analyses for the thermostatic controls and AHU controls, as the installation process and competitors for these two categories of systems differ in several regards. In addition, we also focused on streamlining the gateway installation process and associated costs.

Gateways

During the demonstration project timespan, a significant amount of effort was spent on reducing the installation costs associated with the wireless gateways in each building. Our initial approach was to place each building gateway inside the networking closet/cabinet, allowing it do directly tie into the necessary Ethernet switch. However, due to Air Force requirements stating that no equipment could connect to a network switch without an intermediary jack, this was not allowed. Furthermore, the costs associated with installing the required wall jack for each gateway was expensive since it required utilizing the sole on-base contractor which manages all communications installations.

Power was another concern. Each gateway traditionally uses a wall transformer plugged into a nearby 120V outlet, with the 5V output from the transformer routed to the gateway. This required either a new 120V wire run, or a vulnerable power cable running against the wall.

To reduce the costs associated with the power, we turned to Power over Ethernet (PoE). The majority of the network switches installed at USAF facilities such as Tinker can provide PoE power to end devices. For the demonstration, we utilized a low-cost PoE adapter to provide the necessary 5V power to the gateway, eliminating the need to tie into a 120V connection locally.

We also discovered the majority of the buildings we encountered had unused network jacks in many parts of the building. Most building managers we talked to were more than happy to let us utilize a free jack for the gateway installation. Figure 28 shows a typically gateway mounting. In this example, we utilized an available network port, and installed the gateway in an enclosure mounted directly on the inside wall. Wiremold was used to route the network connection into the enclosure.

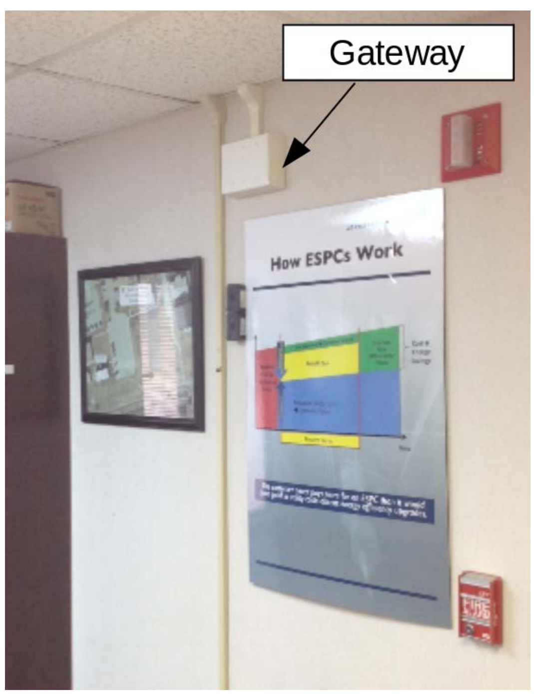

Figure 28. Typical Gateway Mounting

Thermostats

The lowest cost competitor to our wireless BMS for thermostatic applications was determined to be a Zigbee-based wireless thermostat from Viconics. This competing system utilizes a wireless thermostat similar to our approach, however their gateway device is extremely bulky and is not suitable for mounting on interior spaces. As such, both the hardware and installation costs are significantly higher than our wireless BMS on a typical building with 1 thermostat. Table 13 shows this analysis, with the best competitor costing 89% more than our system.

Table 13. Cost Comparison with the Most Cost-effective Thermostat Competitor

Category	Paragon	Viconics
Hardware	$620.00	$1,756.00
Software	$150.00	$150.00
Labor	$360.00	$660.00
Audit/Proposal	$200.00	$200.00
G&A (15%)	$300.00	$415.00
Profit (8%)	$170.00	$254.00
Buffer (10%)	$180.00	$300.00
Total	**$1,980.00**	**$3,735.00**

AHU Controls

When controlling more complex equipment such as AHUs, the most common competing controller is the Niagara JACE. This competing system utilizes JACE controllers to interface with a myriad of different equipment controllers, and connect them to a local network. JACE controllers can also be extended to offer direct equipment control as well. The hardware and licensing costs for this competitor is higher than our system. No secure wireless interface exists for this competitor either, and requires a wired network connection to be made for each controller. Table 14 shows the cost comparison, with the JACE system costing 36% more than our system on a typical building with 2 AHUs.

Table 14. Cost Comparison with the Most Cost-effective AHU Controls Competitor

Category	Paragon	JACE
Hardware	$11,400.00	$21,210.00
Software	$2,100.00	$2,100.00
Labor	$21,690.00	$24,890.00
Audit/Proposal	$800.00	$800.00
G&A (15%)	$5,400.00	$7,350.00
Profit (8%)	$3,311.00	$4,508.00
Buffer (10%)	$4,470.00	$6,086.00
Total	**$49,170.00**	**$66,944.00**

Payback Analysis

A full payback analysis was then run on all buildings at the 38th campus, including buildings which were excluded from the actual demonstration for various reasons. A full installation quote for this group of buildings was created based on an additional full walkthrough by a controls technician. This quote closely matched the example installation costs in the above sections.

The utility savings for each building were calculated based on simulated savings for each building type. For thermostatic buildings, we utilized a building electricity savings of 20% and a gas savings of 40%. These savings were conservatively chosen as around 10% worse than our simulated results.

For buildings with AHUs, we utilized a building electricity savings of 25% and a gas savings of 45%. Again, these savings were conservatively chosen as around 10% worse than our simulated results. Utility rates of $0.055/kWh and $0.49/therm were used.

Table 15 shows the results from the analysis. Nearly all of the buildings were able to achieve a <10-year simple payback. Only 2 buildings could not meet the 10-year simple payback target:

- B4077 and B4078, which are warehouses with no A/C (gas heat only), produced limited savings with a retrofit BMS. Additionally, these buildings had no wired network access, requiring an additional wireless repeater to communicate with a nearby building.

2 additional buildings could only barely meet the 10-year simple payback target:

- B4012 showed a surprisingly low EUI and did not provide as much utility savings as other similar buildings, however was still able to meet a 10-year target.
- B4064 utilized a large number of VAV terminals, making it prohibitively expensive to retrofit the entire building controls. We opted to propose a partial BMS upgrade, which cost less but also produced less utility savings.

Even with these 4 buildings, an overall simple payback of 4.8 years was achieved across the building set (overall installation cost / overall utility savings). Due to the additional benefits the wireless BMS brings to the DoD facility such as improved energy monitoring and O&M, we believe most installations and ESCOs would prefer to bundle the BMS retrofits across the entire set of buildings within the scope of a performance contract.

As part of an unrelated project at Tinker, we have been able to audit approximately 140 other buildings at Tinker and evaluated the installed cost and potential utility savings. The results from this additional investigation have corroborated the results in this report.

Table 15. Simple Payback Analysis on All Demonstration Buildings

Building	Size (sqft)	Electricity Savings	Gas Savings	Total Estimated Savings	Total Savings with 20% Margin	Installed Cost	Simple Payback (yrs)
B4001	2195	$887.67	$214.59	$1,102.26	$881.81	$4,398.00	5.0
B4004	11798	$2,224.40	$896.88	$3,121.29	$2,497.03	$7,592.00	3.0
B4012	14028	$4,163.36	$1,914.64	$6,078.00	$4,862.40	$47,910.00	9.9
B4023	3687	$894.79	$358.12	$1,252.91	$1,002.32	$3,639.00	3.6
B4028	1870	$476.51	$230.24	$706.74	$565.40	$3,692.00	6.5
B4029	19220	$10,251.56	$2,123.71	$12,375.28	$9,900.22	$47,910.00	4.8
B4032	1803	$460.24	$177.15	$637.39	$509.91	$1,877.00	3.7
B4048	2583	$932.96	$494.71	$1,427.67	$1,142.14	$4,093.00	3.6
B4049	3731	$1,163.64	$360.87	$1,524.51	$1,219.61	$3,583.00	2.9
B4057	9898	$7,310.67	$445.97	$7,756.64	$6,205.31	$18,148.00	2.9
B4064	50780	$6,833.85	$3,264.54	$10,098.39	$8,078.71	$78,036.00	9.7
B4068	1483	$249.19	$149.44	$398.64	$318.91	$1,877.00	5.9
B4069	4704	$1,109.66	$454.06	$1,563.72	$1,250.97	$5,584.00	4.5
B4077	2450	$0.00	$142.81	$142.81	$114.24	$4,522.00	39.6
B4078	2428	$0.00	$142.29	$142.29	$113.83	$4,522.00	39.7
B4079	3674	$891.95	$356.88	$1,248.84	$999.07	$2,927.00	2.9
Total	**136332**	**$37,850.45**	**$11,726.91**	**$49,577.36**	**$39,661.89**	**$240,310.00**	**4.8**

Applicability to Larger Buildings

The largest building in the demonstration site was 50,780 sqft, however many larger buildings at Tinker AFB were audited as part of a separate project. In practice, the majority of these larger buildings contained HVAC system which were very similar to B4029, which was retrofit as part of this project. Separate air handler units were typically utilized on every 10-20k sqft of building. Because larger buildings utilized a similar number of AHUs per floor area, the cost savings for any larger building would be similar to the B4012, B4029, and B4064 payback numbers shown in Table 15.

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8 TECHNOLOGY TRANSITION

8.1 IMPLEMENTATION ISSUES

Many of the implementation issues we encountered and addressed during the demonstration were addressed in Section 2.2. This section will primarily list the issues which impeded implementation at the test site, and could be considered part of the difficulty in applying this technology at DoD sites.

Secure Areas

Two of the demonstration buildings contained Sensitive Compartmented Information Facility (SCIF) areas. Wireless devices are forbidden inside the enclaves and within 3 feet outside of the perimeter walls. For our auditing work, we opted to not monitor these SCIF areas as we did not have a non-wireless hardware option at that time.

We initially intended to demonstrate a wired thermostat option for these SCIF area retrofits, but opted against it due to schedule limitations and the limited benefit from the controls retrofit. Paragon does intend to market a wired solution to address these SCIF applications in the near future.

Authority to Operate

For permanent ICS installations on USAF sites, an Authority to Operate (ATO) is required by Air Force Civil Engineering Center (AFCEC). Alternatively, an Interim Authority to Test (IATT) can be obtained for 1-2 year projects. Full ATO approval is then required by the time the IATT expires at the end of the project. Achieving this full ATO was a significant milestone for the project, and the general requirements are described below. We received a full site ATO for the wireless BMS platform at Tinker in May/2017. Note that the DIACAP process was still being utilized by AFCEC at the time of this demonstration. This process will be migrating to the RMF framework in the future, so many of these requirements listed will change.

Changing Site Conditions

During the demonstration, we experienced many site condition changes which limited our testing size. Several of the test buildings had substantial occupancy changes during the demonstration period (e.g., HVAC equipment was shut down after the move, and could not be controlled by our BMS). Furthermore, frequent HVAC equipment failures went without repair for extended periods, invalidating our data during those times.

As a result, our effective sample size of complete control retrofit buildings was reduced from an initial target of 7 to only 4 buildings. Given the age of the typical DoD facility, and our observations on mission changes during the demonstration, we anticipate future projects should plan for similar site condition changes.

For this project, we were able to overcome the reduced sample size by utilizing high-resolution simulations to effectively fill in the data holes. By extending the initial baseline period for data capture, we were able to obtain a sufficient amount of performance data in all buildings, enabling us to build good simulation models for all buildings in our scope.

8.2 COMMERCIALIZATION

All hardware and software products utilized in this demonstration are currently in production and available for sale as of Q4/2017. During the process of this ESTCP demonstration, we began to modify the initial technology transition plan for the technology. In trying to tailor the technology for use with performance contracting, a significant need for additional support services related to metering, auditing, controls installation, and M&V became apparent. Paragon is currently working with another ESCO for a larger rollout of the wireless BMS platform as part of an ESPC at Tinker. As part of this project, Paragon has already included support services into their offerings, with specific focuses on the following areas:

- Metering Management: Overseeing metering installation plans, installation, and collection needed to provide energy baselines for auditing phases
- EMS Design: Auditing buildings for fixed price proposals to implement the wireless BMS technology at sites.
- M&V: Long-term support for metering collection, BMS performance monitoring, and cybersecurity management over the course of the contracts.

We believe the inclusion of these services is critical in accelerating the adoption of the technology for DoD customers. By matching "end-to-end" support services with the end-to-end capabilities of the wireless platform, a single contractor can potentially manage much of the related efforts required for ESPCs and UESCs.

9 REFERENCES

Murphy, John "Using Time-Of-Day Scheduling to Save Energy" ASHRAE Journal, May 2009 https://www.ashrae.org/File Library/docLib/eNewsletters/murphy--052009--feature.pdf

The technology used in this demonstration is well documented on Paragon Robotics' website, and can be viewed in the Support section of the website using the following link: http://paragonrobotics.com/halo-s/?jumpToTab=helpViewer

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APPENDIX A POINTS OF CONTACT

Point of Contact Name	Organization Name	Phone & E-mail	Role in Project
Julian Lamb	Paragon Robotics	330.977.7981 julian.lamb@paragonrobotics.com	Co-PI
Tony Colonnese	Ameresco	781.775.7365 acolonnese@ameresco.com	Co-PI
Al Romero	USAF 72nd CE	405-209-5269 albert.romero@us.af.mil	Tinker AFB CE Energy manager (retired Jan/2018)
Joey Hunter	USAF 72nd CE	405-734-7213 joey.hunter@us.af.mil	Tinker AFB CE Energy manager
Thanh Alcorn	USAF 38th CEIG	405-734-7467 thanh.alcorn@us.af.mil	Site facility manager (38th CEIG)

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APPENDIX B BASELINE DATA

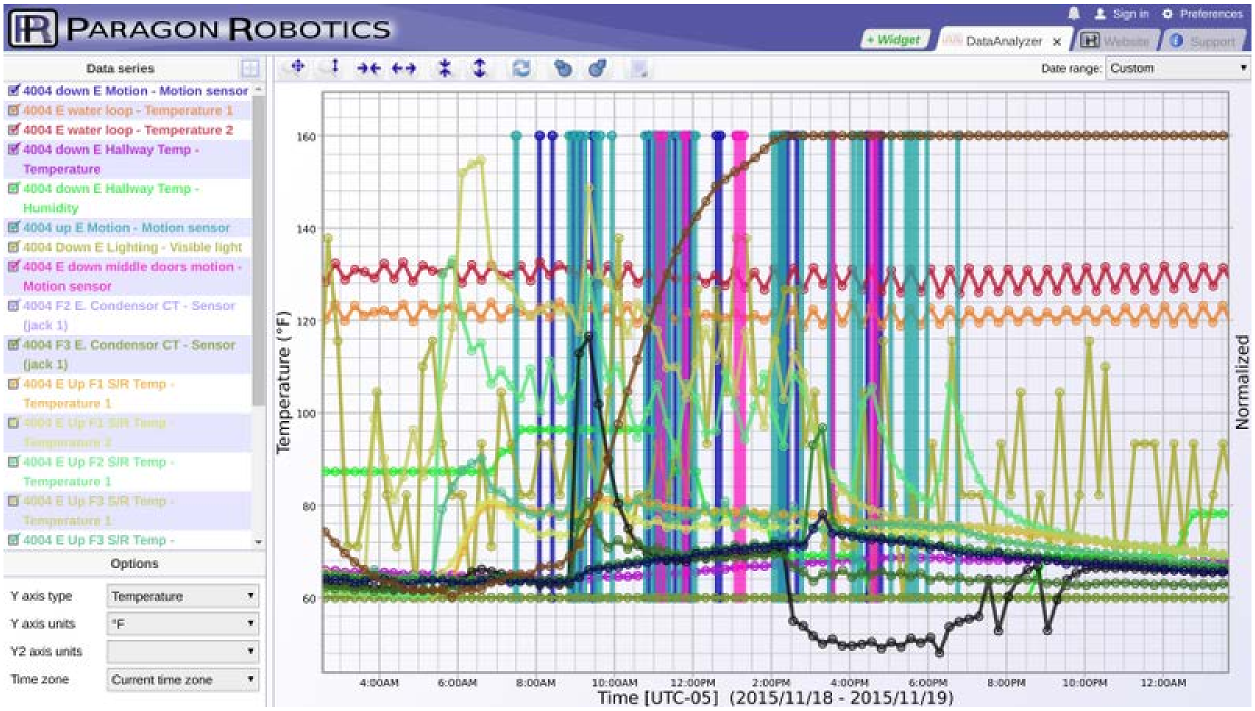

Figure 29. Sample Measured Baseline Data for B4004 East

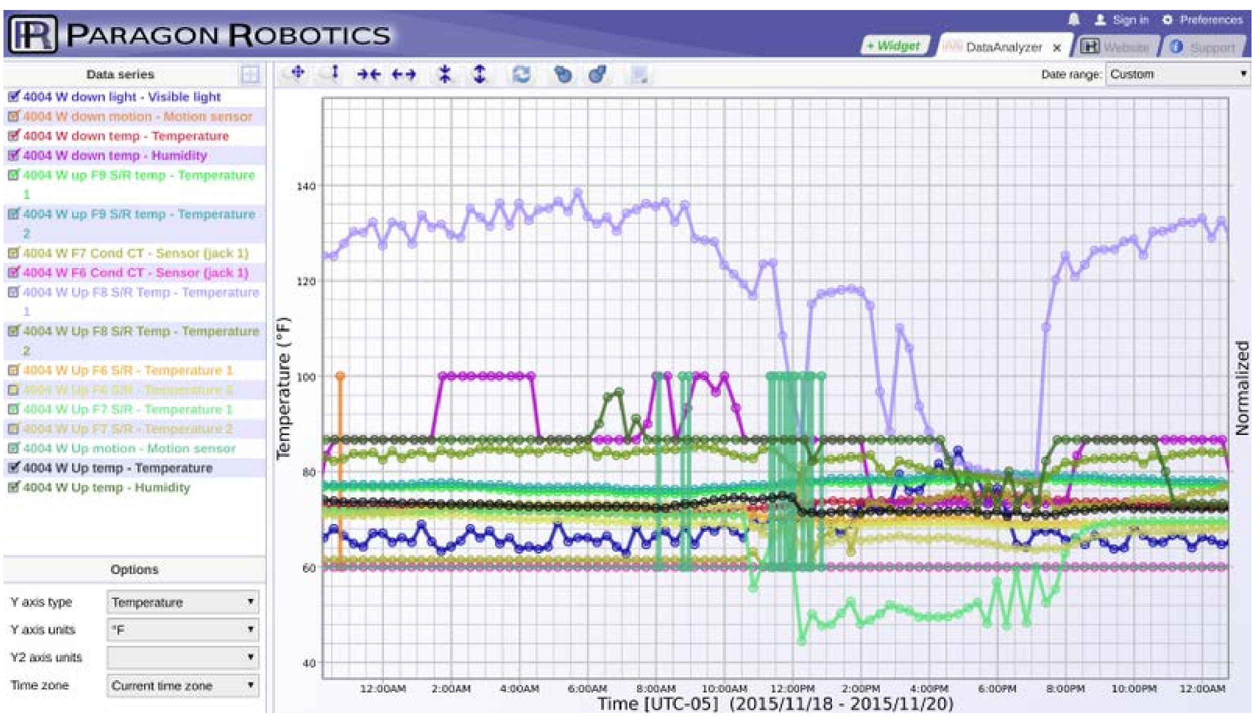

Figure 30. Sample Measured Baseline Data for B4004 West

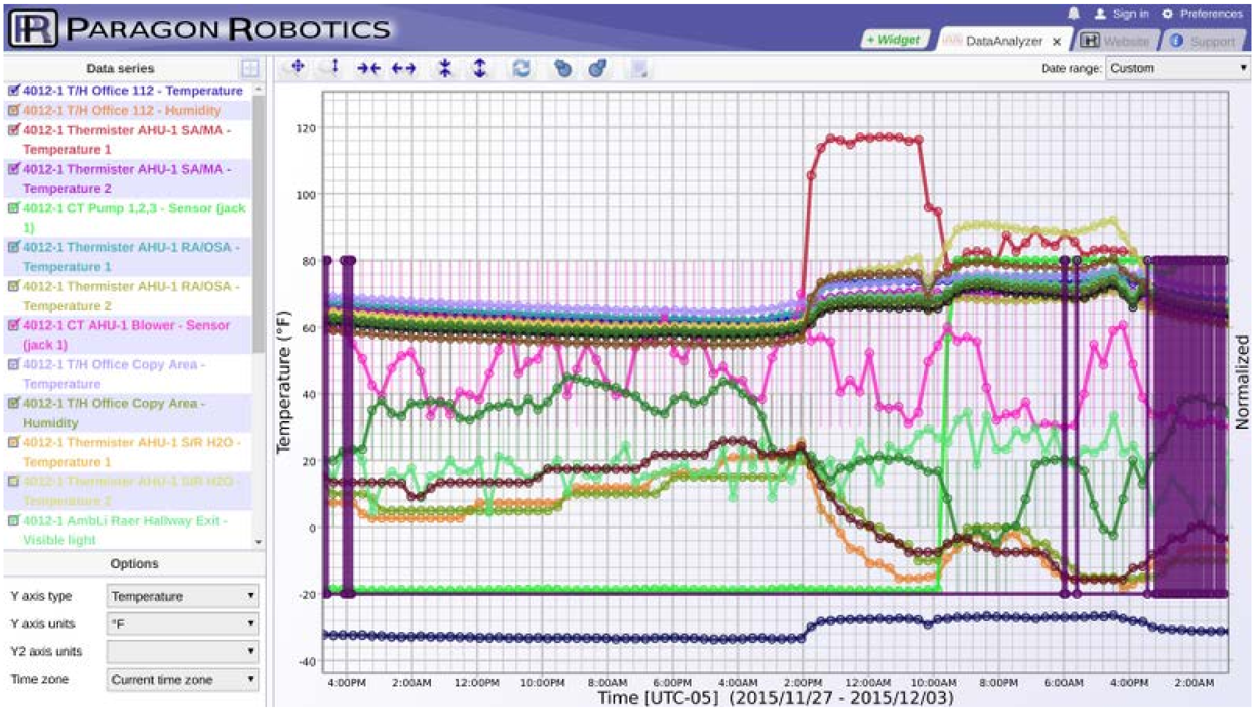

Figure 31. Sample Measured Baseline Data for B4012-1

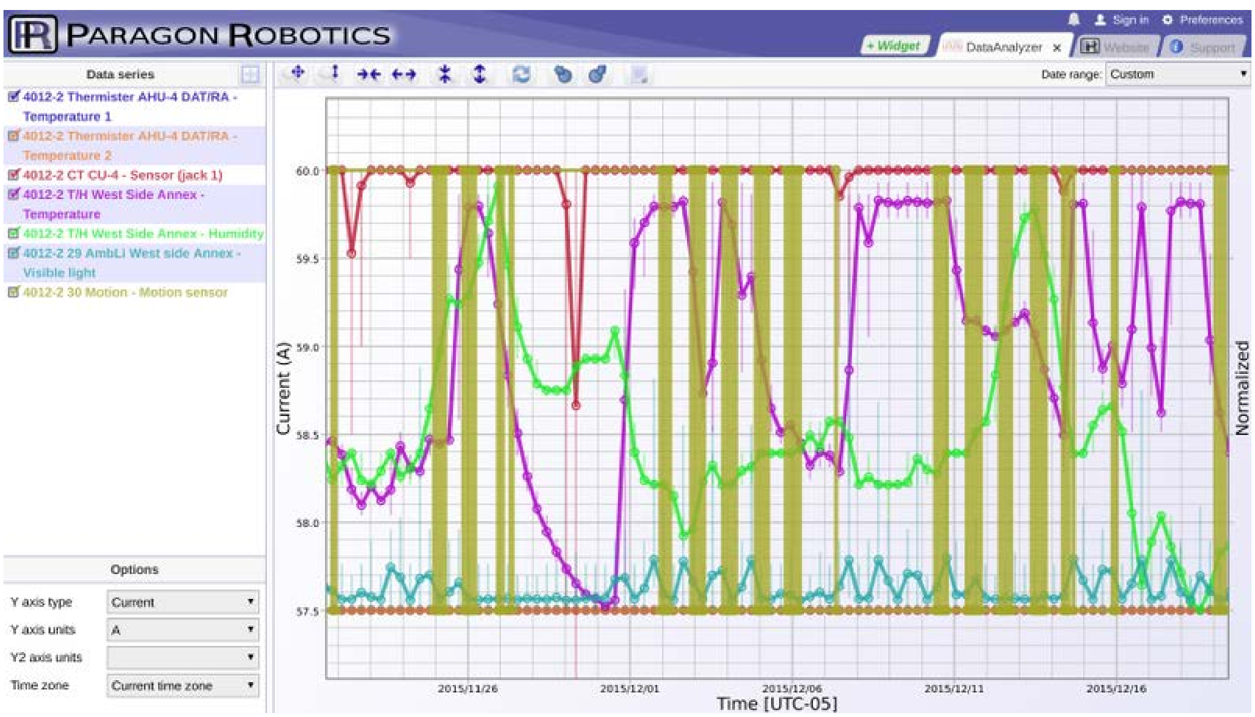

Figure 32. Sample Measured Baseline Data for B4012-2

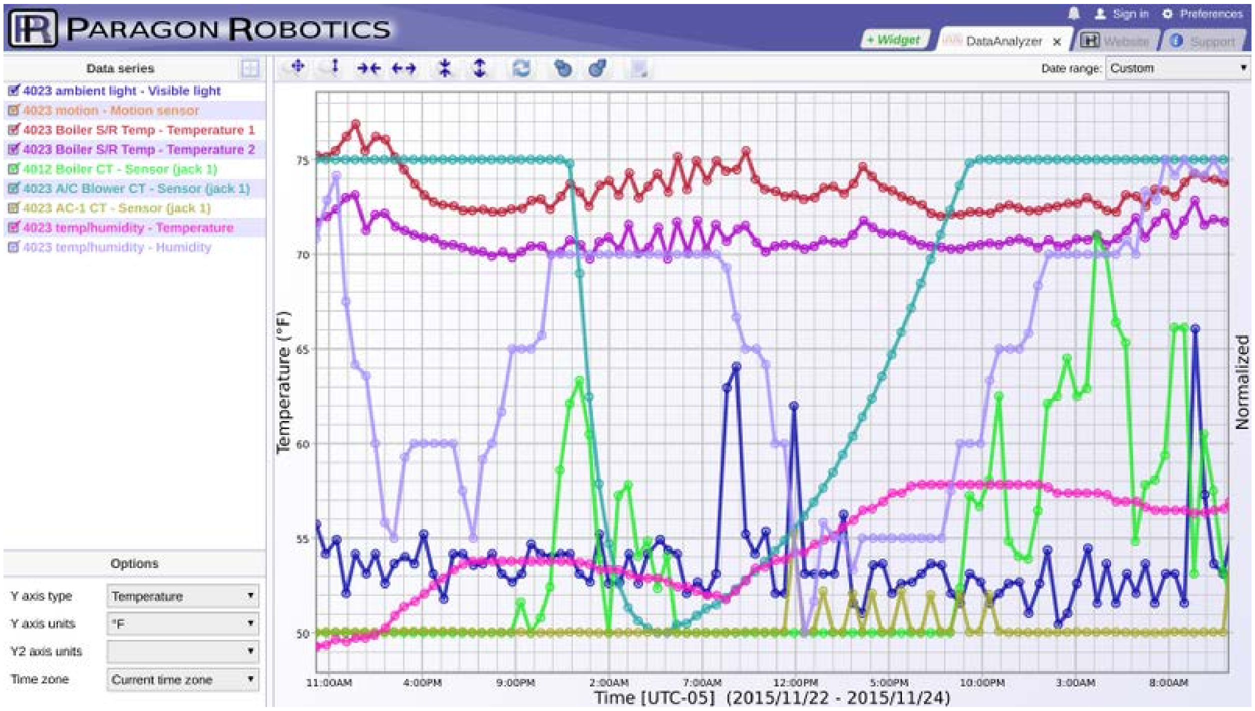

Figure 33. Sample Measured Baseline Data for B4023

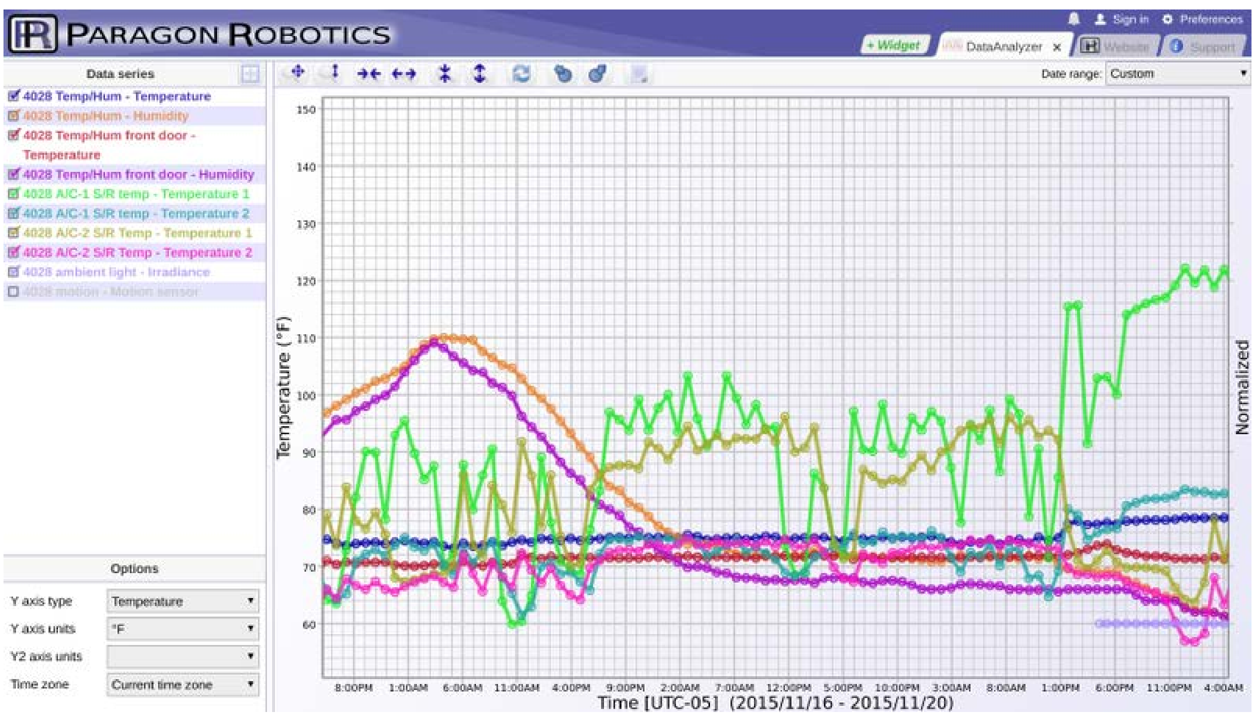

Figure 34. Sample Measured Baseline Data for B4028

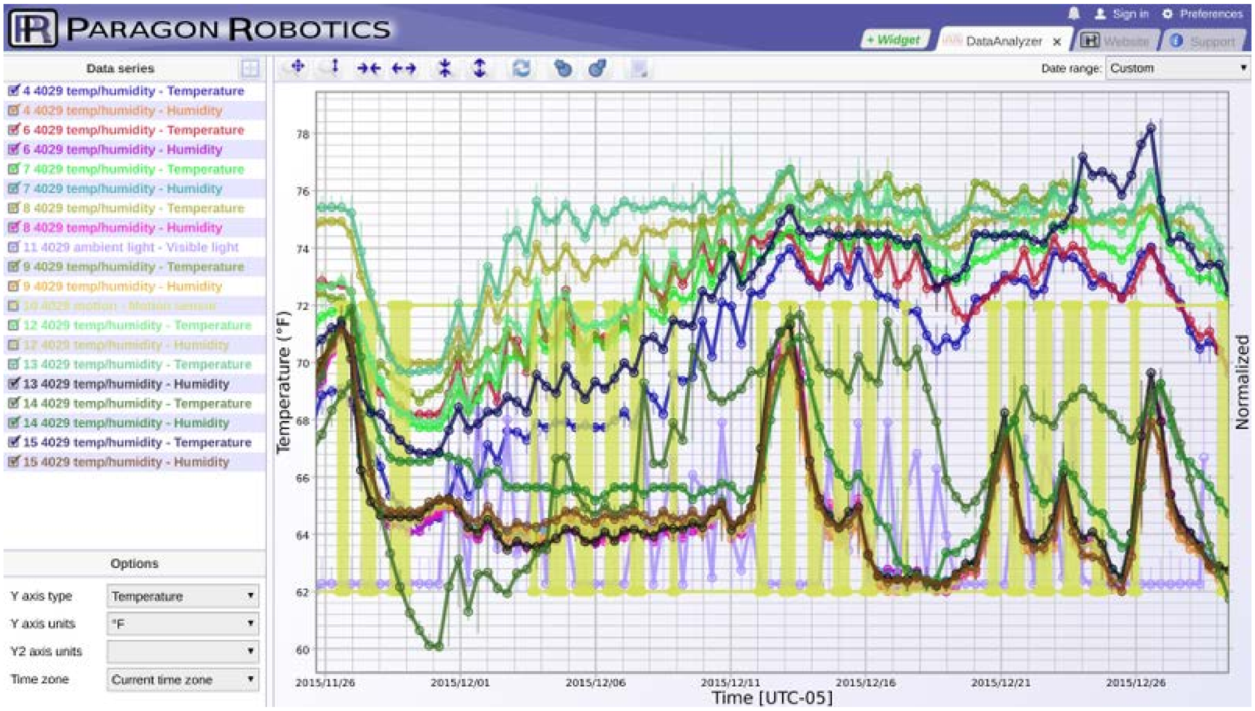

Figure 35. Sample Measured Baseline Data for B4029-1

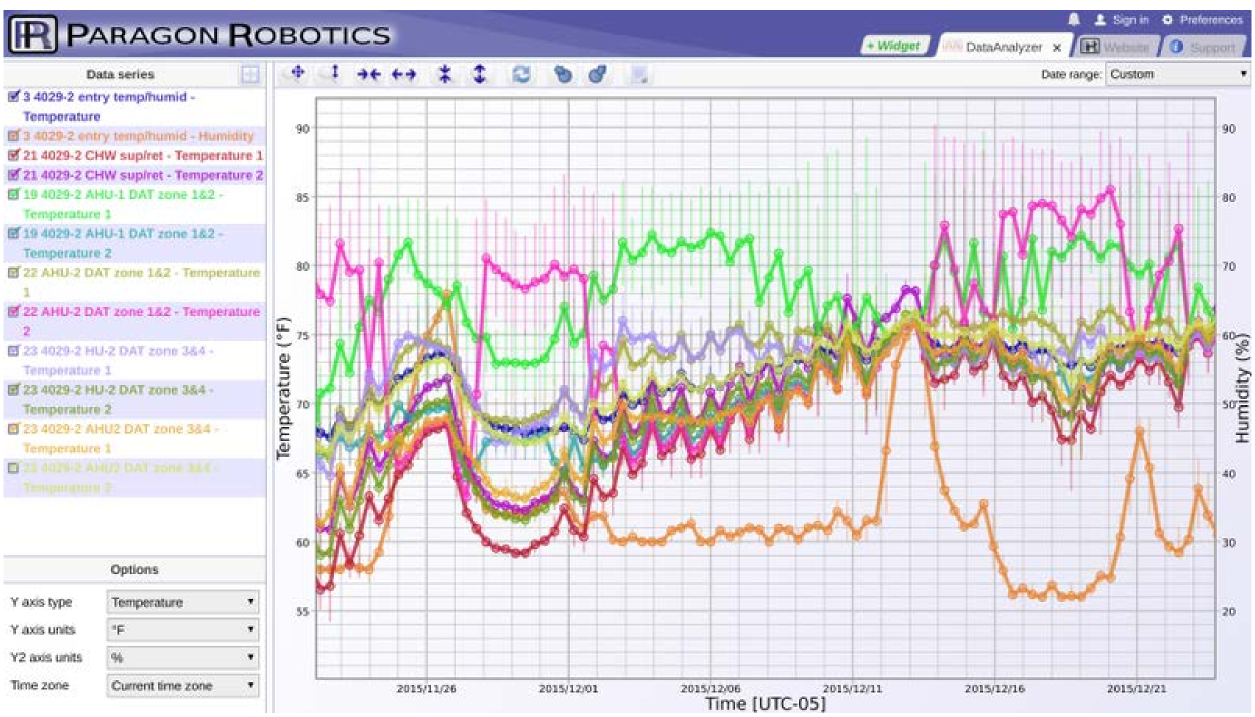

Figure 36. Sample Measured Baseline Data for B4029-1

Figure 37. Sample Measured Baseline Data for B4032

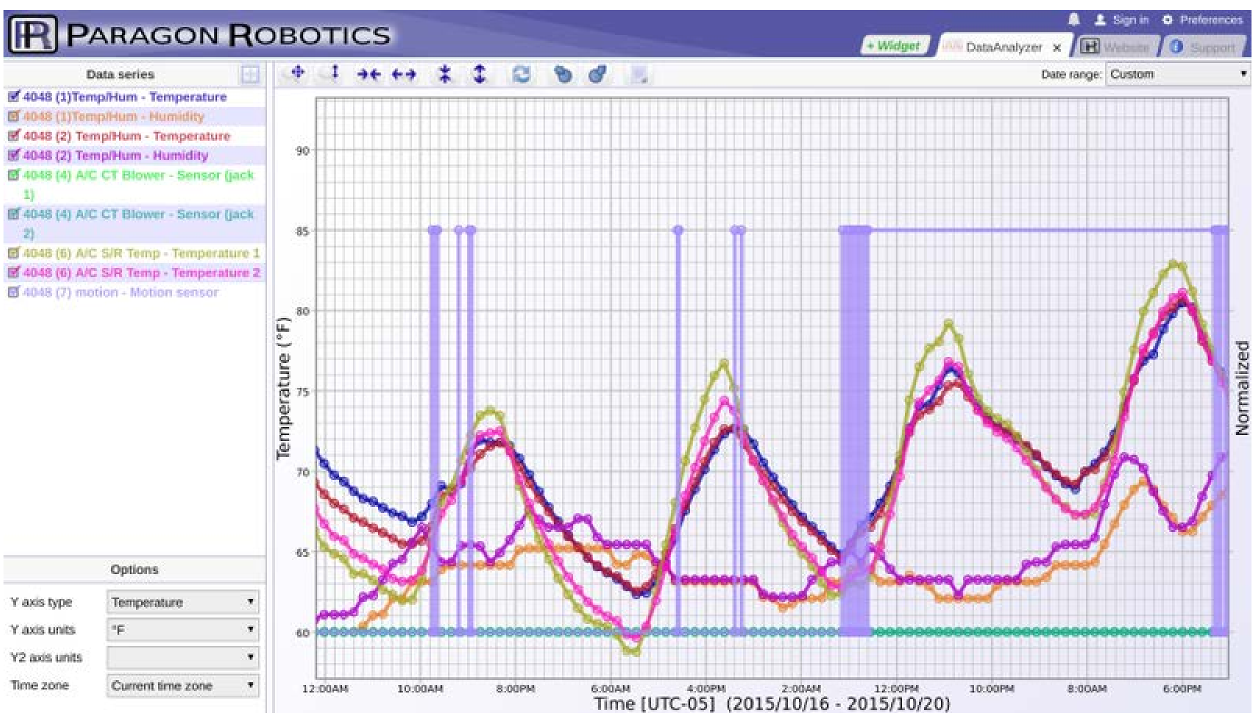

Figure 38. Sample Measured Baseline Data for B4048

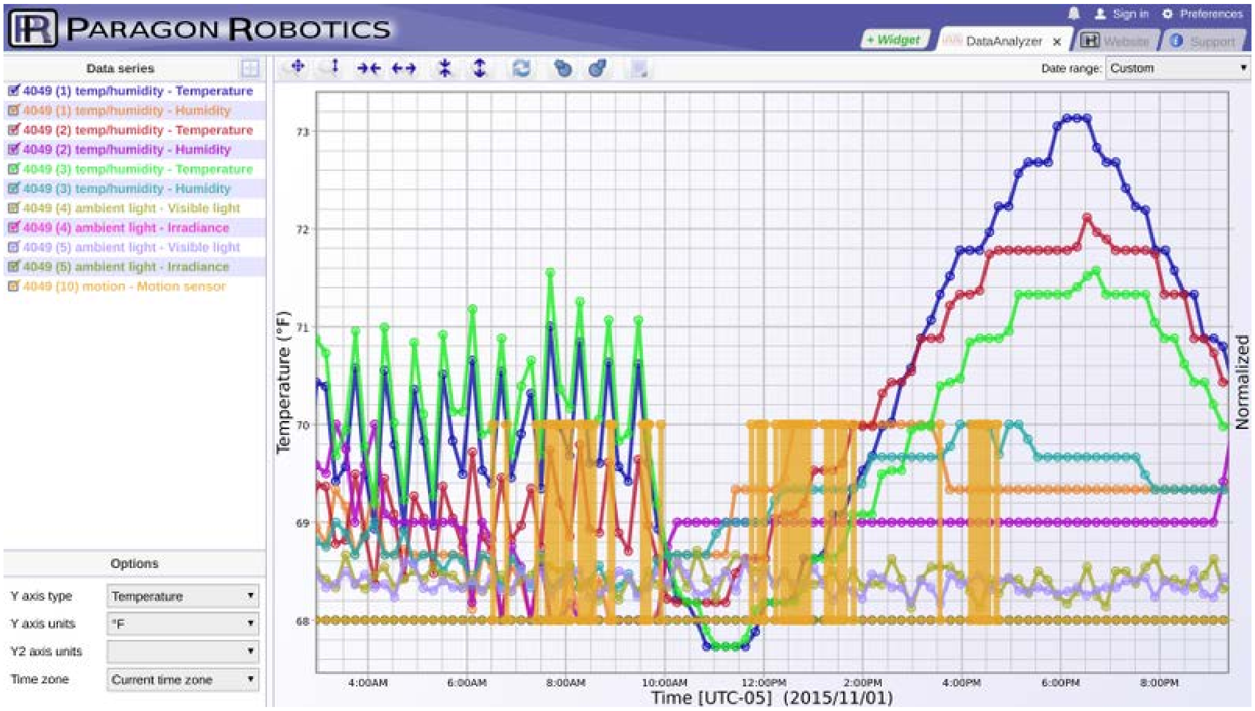

Figure 39. Sample Measured Baseline Data for B4049

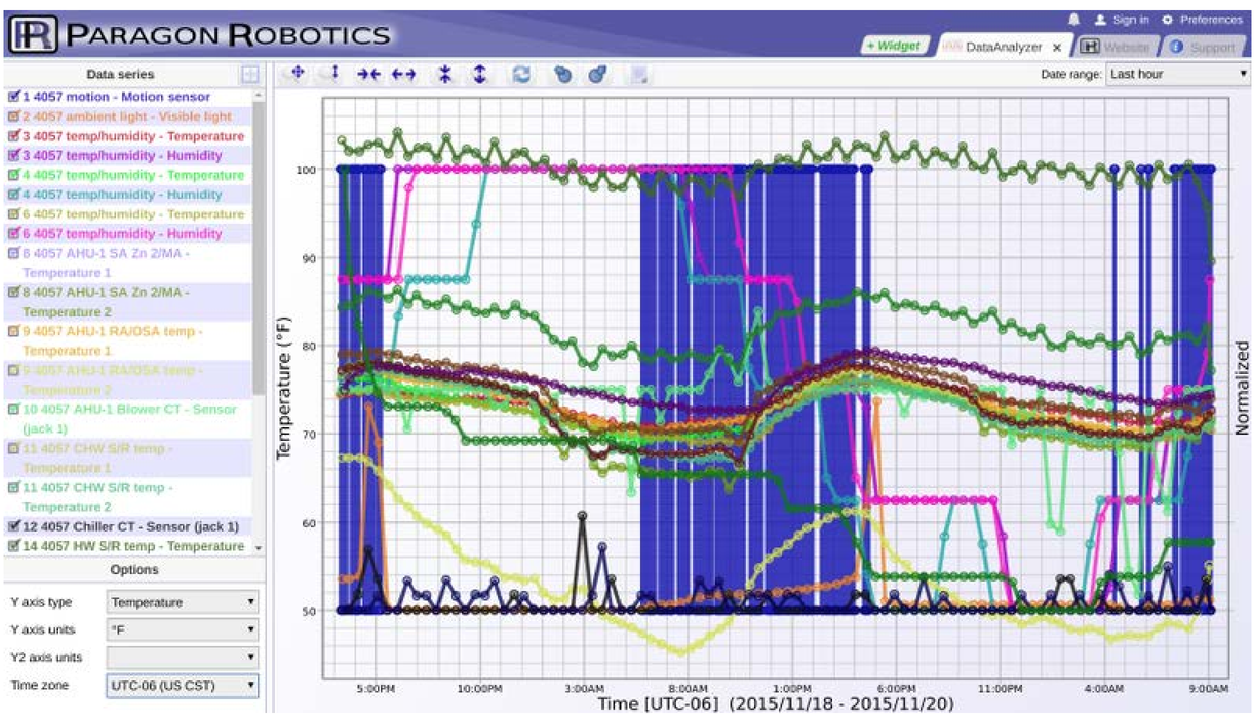

Figure 40. Sample Measured Baseline Data for B4057

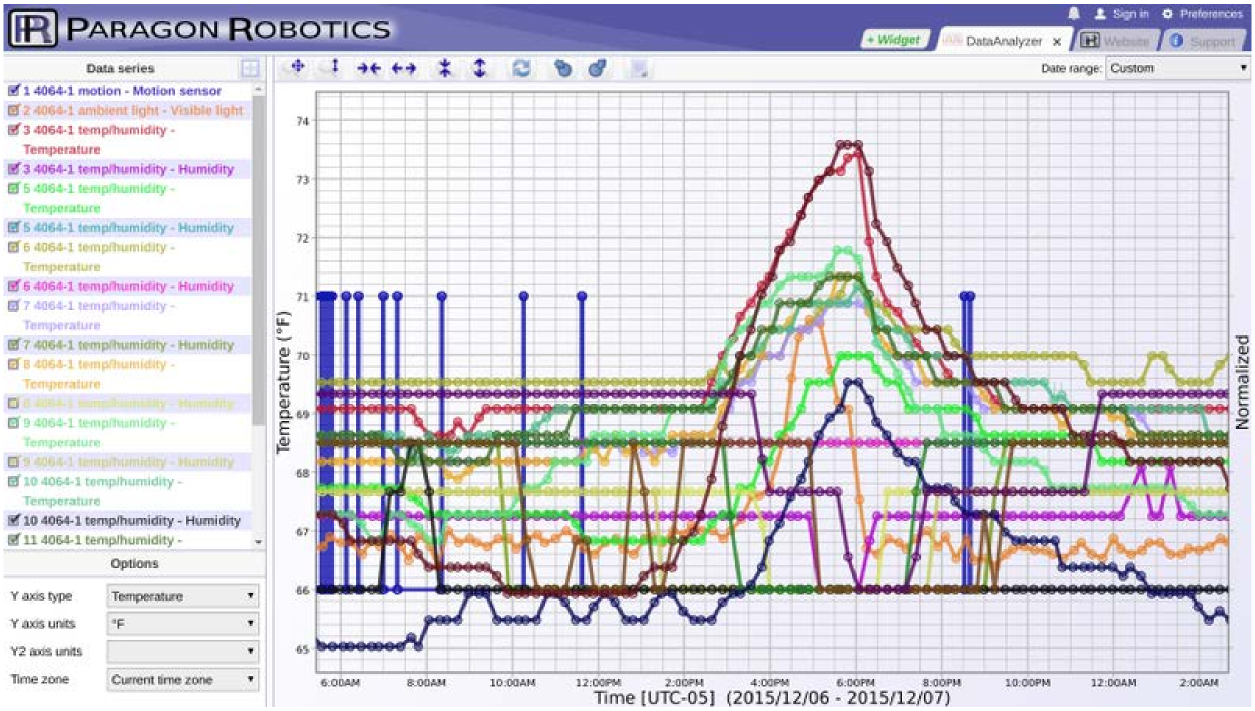

Figure 41. Sample Measured Baseline Data for B4064-1

Figure 42. Sample Measured Baseline Data for B4064-2

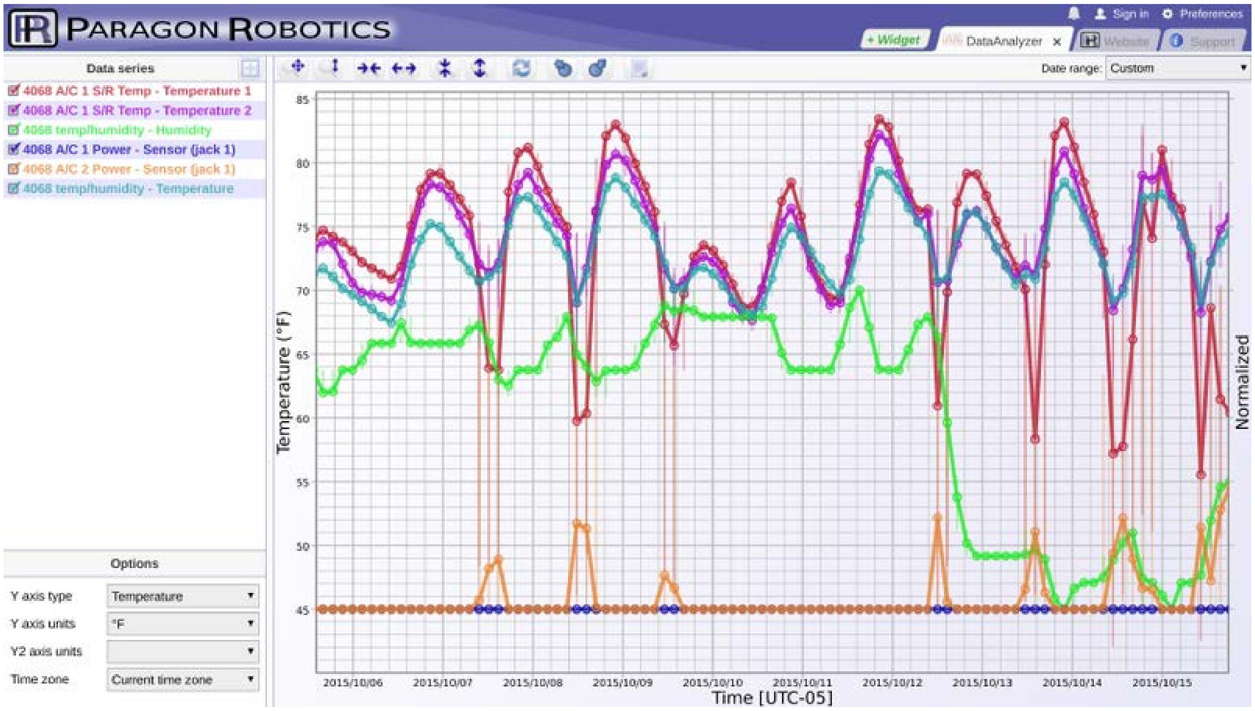

Figure 43. Sample Measured Baseline Data for B4068

Figure 44. Sample Measured Baseline Data for B4069

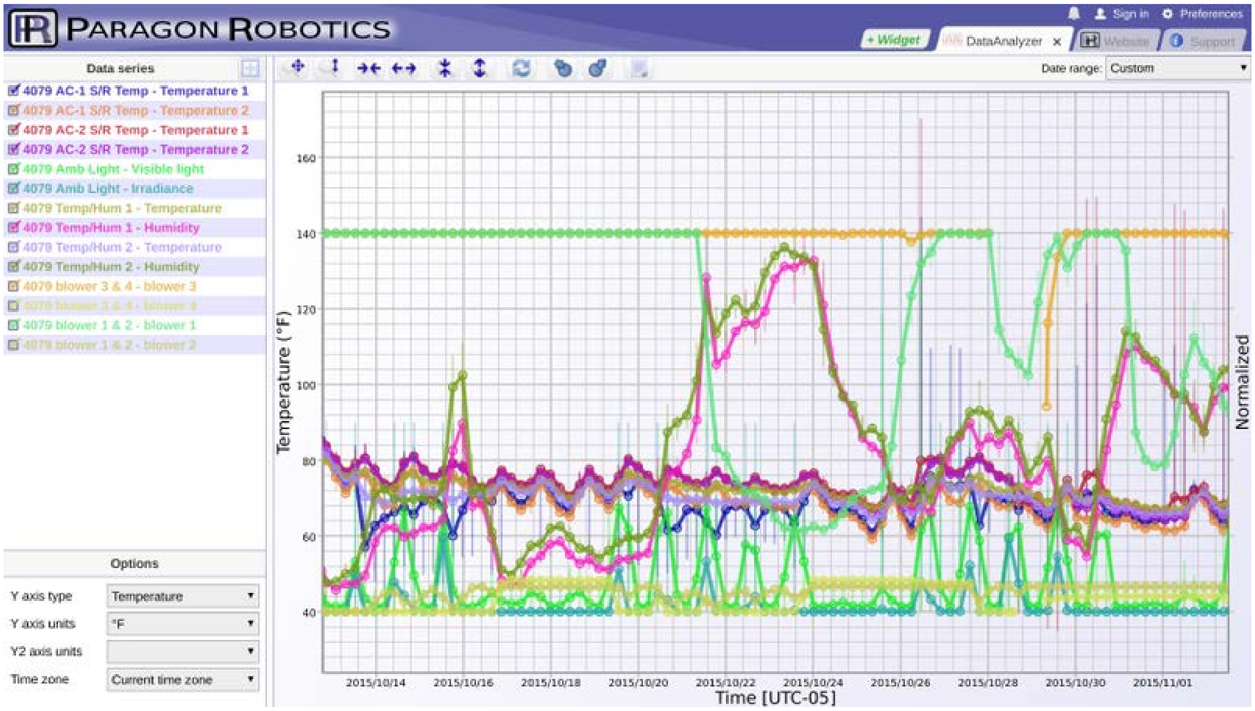

Figure 45. Sample Measured Baseline Data for B4079